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THESIS

FREE SPACE OPTICAL COMMUNICATION IN THE MILITARY ENVIRONMENT

by

Charles Casey

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13. ABSTRACT (maximum 200 words)

Free Space Optical (FSO) communications use modulated collimated light energy, usually in the form of an infrared (IR) laser, to transmit data. This affords FSO many appealing qualities such as a very high bandwidth capability, a high level of security through a low probability of detection (LPD) and a low probability of intercept (LPI), and a signal that is impervious to radio frequency (RF) interference or regulation.

Military communications require broadband capabilities at the highest level of security in an incredibly dense RF operating environment. The bandwidth and security qualities of FSO make it an attractive technology for military communications. However, a strict line of sight (LOS) requirement and link attenuation in poor atmospheric conditions limit its application.

Several companies are developing and implementing FSO communication solutions worldwide in response to a demand for broadband connectivity without RF interference at a relatively low price point. Recent advances in hybrid FSO-RF systems have improved performance in all atmospheric conditions. This research conducts a survey of the current state of FSO communications and analyzes its suitability as a military communication solution. The findings indicate further research, development, and link performance improvement is required before actual implementation of FSO communications can occur.

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FREE SPACE OPTICAL COMMUNICATION IN THE MILITARY ENVIRONMENT

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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LIST OF ACRONYMS AND ABBREVIATIONS

AHP	Analytical Hierarchy Process
AFRL	Air Force Research Laboratory
BER	Bit Error Rate or Bit Error Ratio
CI	Compact Interrogator
COP	Common Operational Picture
COTS	Commercial Off The Shelf
DARPA	Defense Advanced Research Projects Agency
DII	Direct Interrogator-to-Interrogator
DMOI	Dual Mode Optical Interrogator
EDRS	European Data Relay System
ESA	European Space Agency
FALCON	Fast Airborne Laser Communications Node
FBCB2	Force XXI Battle Command Brigade and Below
FCC	Federal Communications Commission
FDA	Food and Drug Administration
FMV	Full Motion Video
FOB	Forward Operating Base
FOENEX	Free-Space Optical Experimental Network Experiment
GBOSS	Ground Based Operational Surveillance Systems
GEO	Geostationary Orbit
GSA	General Service Administration
HD-SDI	HDTV Serial Digital Interface
HDTV	High-Definition Television
IDU	Indoor Unit
IEC	International Electrotechnical Commission
IR	Infrared
ISR	Intelligence, Surveillance, and Reconnaissance
ITT	International Telephone and Telegraph
JIFX	Joint Interagency Field Exploration
LADEE	Lunar Atmosphere and Dust Environment Explorer

LED	Light Emitting Diode
LEO	Low Earth Orbit
LLCD	Lunar Laser Communication Demonstration
LOS	Line of Sight
LPE	Low probability of Exploitation
LPD	Low Probability of Detection
LPI	Low Probability of Interception
MWR	Morale Welfare and Recreation
MRR	Modulating Retro-reflector
OOK	on-off keying modulation
PAT	Point, Acquire and Track
PB	Patrol Base
PPM	pulse-position modulation
PTDS	Persistent Threat Detection Systems
RF	Radio Frequency
SC	Subscriber Connector
TALON	Tactical Line-of-Sight Optical Network
TAP	Tracking, Acquisition and Pointing
TBMCS	Theater Battle Management Core Systems
TCP	Transmission Control Protocol
TOGS	Transportable Optical Ground Station
UAV	Unmanned Aerial Vehicle
UDP	User Datagram Protocol
VMC	Visual Meteorological Conditions
VoIP	Voice Over Internet Protocol
WDM	Wave Division Multiplexing

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I. INTRODUCTION

A. INCREASING DEMAND FOR BANDWIDTH ON THE BATTLEFIELD

Demand for bandwidth on the battlefield has increased significantly in the past 20 years. The primary means of communication between higher commands and subordinates has shifted from radio and voice to chat message and email. Data-rich multimedia content, such as high-definition pictures, video chat, video files, and PowerPoint briefings, are being sent at nearly every level of the chain of command. It is not uncommon for one user to have three different systems accessing three different networks. Networked systems such as Force XXI Battle Command Brigade and Below (FBCB2) and Theater Battle Management Core Systems (TBMCS) provide commanders throughout the battlespace with a synchronized, near real-time and customizable common operational picture (COP). The introduction of full-motion video (FMV) via numerous different Intelligence Surveillance and Reconnaissance (ISR) systems, such as targeting pods on aircraft, Ground Based Operational Surveillance Systems (GBOSS) towers, and Persistent Threat Detection Systems (PTDS), have increased the demand for network bandwidth considerably. The commander’s need to view these FMV feeds for areas even outside of their own battlespace triggered widespread availability and accessibility. As a result, there is widespread abuse. A large amount of bandwidth is consumed to stream live FMV feeds by curious individuals that do not necessarily need to see the FMV but have access to the feed. This phenomenon, commonly referred to as “predator porn,” further exacerbates the bandwidth shortage problem. It is not uncommon to walk into a Combat Operations Center (COC) and see multiple FMV feeds streaming simultaneously. Oftentimes, this is done with no significant information disseminated, or even with no one watching the feed.

Fiber-optic cable technology is more than capable of meeting the military’s current bandwidth demand. However, in most tactical networks it is

not feasible to run cable from one node to another. In order to run and maintain the required cable, communications personnel would have to be placed in harm's way. Furthermore, securing the cable from the enemy would be a monumental undertaking. These factors and the associated logistics and cost of laying cable make wireless communication methods the most favorable choice for tactical applications.

1. Radio Frequency (RF) Wireless Communication Shortfalls

Current RF systems are not able to keep up with increasing bandwidth demands. For example, the AN/MRC-142C is capable of streaming about 16 Mbps over a distance of roughly 50 kilometers [1]. This is sufficient for streaming FMV but not multiple feeds simultaneously with other data transmissions. The problem with bandwidth extends to ad hoc networking, where the number of nodes in a network is limited by the amount of bandwidth available and the protocols implemented. Furthermore, RF communications present a real challenge to security due to their high probability of detection and interception resulting from wide area propagation of the signal. Directed RF can be used to mitigate this to some degree but not to a level anywhere near that of collimated laser energy. In addition, operating on RF signals requires deconfliction through the Federal Communications Commission (FCC) and its respective organizations in foreign nations, as well as adjacent units in RF dense operating areas.

2. Free Space Optical (FSO) Wireless Communications Advantages

Current terrestrial FSO systems are capable of delivering near fiber-like performance of 10 Gbps over a range of 50 km [2]. Additionally, extraterrestrial FSO systems are capable of transmitting a 5.5 Gbps signal at distances of hundreds of thousands of kilometers [3]. This performance gap over RF in bandwidth is accomplished by modulating eye-safe laser light. Utilizing laser light as a communication medium allows the user to accurately focus the

transmission signal directly onto the intended receiver. This, in turn, offers a very high level of security through a low probability of detection (LPD) and low probability of interception (LPI). Furthermore, the FCC does not regulate laser light and the signal is much easier to deconflict than RF signals.

B. FSO IMPLEMENTATION

The implementation of FSO technology in civilian and military communication infrastructures has been slow to catch on. High cost combined with fairly high signal attenuation and low availability of early systems have been major barriers to FSO employment in the past. However, due to the potential available bandwidth and the absence of federal regulation, FSO is still seen as an attractive solution. Consequently, a great deal of money and time has been spent improving this technology. Advanced software and hardware techniques have improved link performance. Hybrid systems, those that incorporate an RF backup, have increased availability up to 99.999% even in unfavorable atmospheric conditions [4].

C. PROBLEM STATEMENT

The bandwidth demand in today's battlespace continues to increase as more ISR sensors and networked information systems are introduced. Current RF wireless technologies are barely able to keep up with the bandwidth and range requirements of today's military digital communications. This thesis investigates FSO communication systems as a possible solution to the military's bandwidth issues due to their high data rates, high level of security through LPI and LPD, and ease of use.

D. SCOPE AND BOUNDARIES

The goal of this thesis is to provide the reader with a sufficient enough understanding of FSO to make informed decisions on the readiness of FSO as a possible military communication solution. The thesis provides a thorough background of FSO technology as well as an unclassified taxonomy of

successful FSO systems in both commercial and experimental applications. It then suggests some tactical scenarios where FSO implementation would be most effective. The thesis opens the door for future work exploring specific FSO implementation in greater detail.

E. FSO'S RELEVANCE TO THE DEPARTMENT OF DEFENSE

The Department of Defense is bandwidth constrained with respect to medium-to-long range (beyond a few kilometers) tactical communications. Typically, broadly dispersed units more than a few kilometers away are limited to RF communication solutions designed for voice transmissions and only capable of data transmissions less than a few Mbps. It has identified this capability shortfall and is looking for replacement technologies for current RF solutions [1]. FSO allows for line-of-sight (LOS) digital communications at ranges comparable to RF counterparts. FSO also offers bandwidths that far exceed those available from RF technologies at the distances required. Perhaps most appealing of all is the level of security that is achieved through FSO implementation due to its LPD and LPI. Furthermore, it does so without exacerbating an already very dense RF operating environment.

F. THESIS ORGANIZATION

The remainder of this thesis is organized as follows. Chapter II provides background regarding FSO technology. It begins with a brief history, addresses the capabilities and limitations, and ends with a discussion of general FSO system construct. Chapter III is a taxonomy of current FSO systems as well as an introduction to the Analytical Hierarchy Process (AHP) as a means of choosing an appropriate system for a specific application. The chapter organizes the FSO systems into three broad categories: static, dynamic and space-based. Chapter IV describes scenarios that would be most advantageous to FSO implementation with current systems. Finally, Chapter V includes the conclusion and recommendations for future exploration and development of FSO communication capabilities.

II. BACKGROUND

This chapter provides the reader with a thorough understanding of Free Space Optics (FSO) as a means of communication. It begins with a brief discussion on the history of FSO and moves into the advantages and disadvantages of FSO over more traditional forms of digital communication methods, such as radio frequency (RF) and copper wire. Finally, the general makeup, components, and techniques used to construct an FSO communication system and how the environment can affect performance are discussed.

A. A BRIEF HISTORY OF FSO

Optical communication is one of the earliest forms of communication. Theorists believe early humans used hand and arm signals to communicate as language was developed [5]. To this day, this form of rudimentary optical communication is used between two parties that do not share a common language. As the need to communicate over long distances emerged, specifically those distances outside of the audible range, more sophisticated forms of optical communication were developed to meet the requirement. The most fundamental of these methods used fire to make smoke or light that could be seen over long distances during either day or night. A famous example of this is the reporting of British troop movements in Boston during the initiation of Dawes and Revere’s ride at the beginning of the American Revolutionary War. One lantern in the sexton of the North Church meant that the British were making movement by land, and two lanterns meant that they would move by water on the Charles River [6].

Even much earlier than Paul Revere’s ride, optical communication had developed into the semaphore or optical telegraph. The optical telegraph utilized a system of towers located within line of sight of one another. Messages were passed from one tower to the next using some form of communication protocol. One of the earliest examples of the optical telegraph was used in

Greece around 200-125 B.C. [7]. The invention of the telescope greatly improved the optical telegraph by allowing the towers to be placed considerably further apart. The most extensive use of the optical telegraph occurred in France during the reign of Napoleon Bonaparte [7]. Eventually, the optical telegraph was replaced by the electromagnetic telegraph, but it was in use in Algeria until 1860 and in some very remote areas until the early 1900s [7]. The heliograph, which is an optical telegraph that transmits Morse code wirelessly by reflecting flashes of sunlight, was used by the Pakistani military until 1975 [8]. Some other forms of basic optical communication that are still commonplace today include semaphore flags and signal lamps utilized by navies around the world, as well as Aldis lamp signals used by aircraft controllers to communicate to pilots in the event of radio failure.

Figure 1. An air traffic controller signals with an Aldis lamp, from [9].

The first successful voice transmission on a beam of light occurred in 1881 via an invention called the photophone developed by Alexander Graham Bell and Charles Sumner Tainter [10]. This message was transmitted between two buildings nearly 200 meters apart. The photophone was similar to the recently invented telephone, except where the telephone functioned by modulated electricity over a wire circuit, the photophone operated wirelessly by means of modulated light. Bell believed that the photophone was "the greatest invention he had ever made, greater than the telephone" [11]. Nevertheless, the telephone, radio and telegraph dominated telecommunications, and all efforts

were focused on further developing those technologies. The photophone was the first instance of FSO as we think of it today and the precursor to fiber optics.

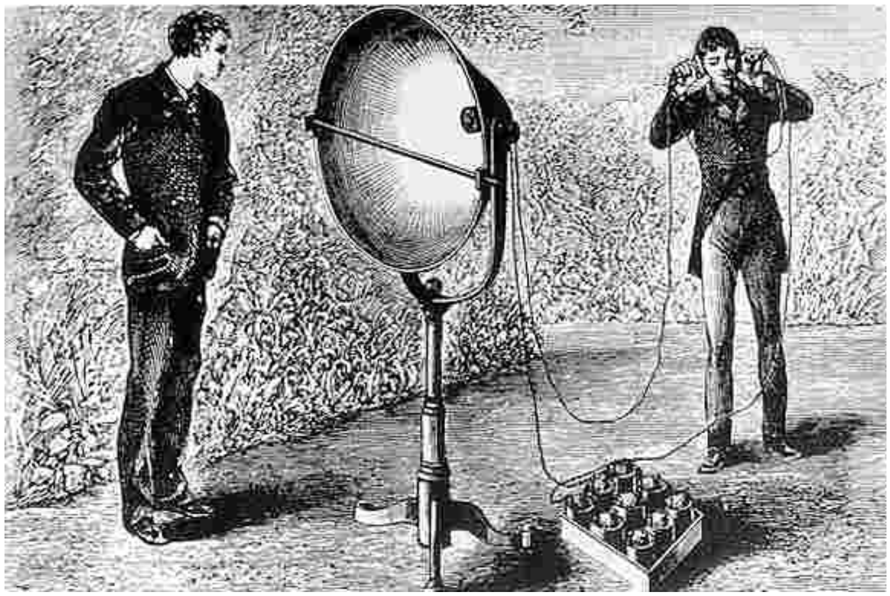

Figure 2. A photophone receiver, from [12].

The invention of the laser in 1960 piqued interest in the development of FSO during the ’60s and ’70s, especially by military organizations. However, the introduction of fiber optics in the 1980s again diverted attention away from the development of FSO. Recently, due to advances in technology, and a renewed realization of the benefits that FSO offers, significantly more research is being done in the area.

FSO technologies are beginning to catch on due to their relatively low cost, expedient setup time, high bandwidth, and proven performance. In the late 1990s and early 2000s there were several commercial applications of FSO. According to an article published by *USA Today*, Merrill Lynch used FSO systems to set up ad-hoc networks to reconnect its Lower Manhattan office to its data centers in New Jersey and Midtown Manhattan after the terrorist attacks in 2001, and the law firm Mayer Brown and Pratt also used FSO systems to open up 400 phone lines for their clients displaced in the attacks [13]. This article

went on to discuss Sweden and Spain both having commercial carriers that offer broadband access via FSO. Additionally, the University of Seattle uses FSO to connect its 6000 students and 1000 faculty members throughout the campus [13]. Also in Seattle, the Four Seasons Hotel as well as the Preston and Gates Ellis law firm use FSO to access and offer broadband connections. According to the manager at the Four Seasons Hotel, they have experienced only one outage that lasted just a few moments following a magnitude 6.8 earthquake and there has been absolutely “no weather related outages.” The success of FSO in Seattle, where fog is typically heavy, is an invaluable indicator of the potential of the technology [13].

A common commercial use-case implements FSO as a solution to the last mile problem. Utilizing FSO in this fashion prevents the dramatic losses resulting from transferring the signal from the fiber backbone onto the copper wire infrastructure [14]. Only a small percentage of buildings have access to the fiber backbone. In urban areas, where buildings are in close proximity to one another, a significant percentage of buildings are within a workable FSO implementation range to the buildings that do have direct access to the fiber backbone. Figure 3 shows a typical commercial FSO solution to the last mile problem.

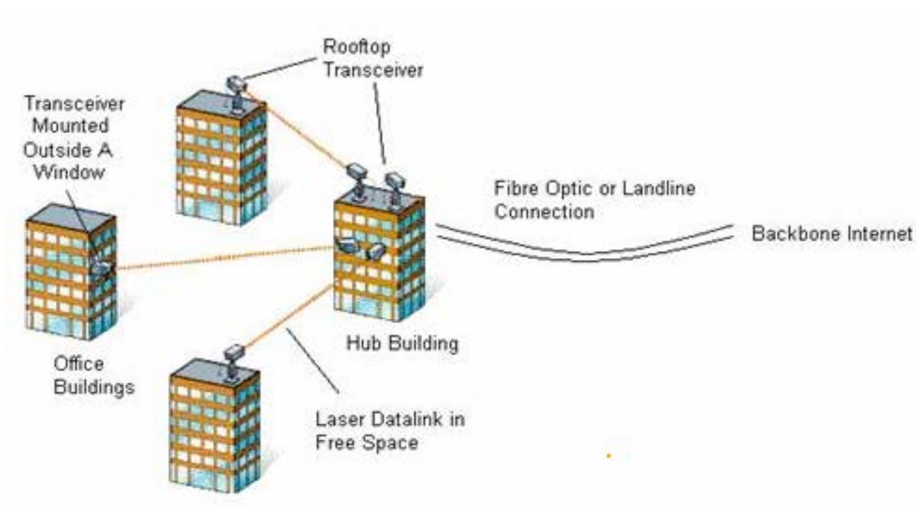

Figure 3. Typical commercial FSO network configuration, from [14].

The United States Air Force in collaboration with ITT Advanced Engineering and Sciences has developed an airborne laser crosslink known as the Fast Airborne Laser Communications Node or FALCON (Figure 4). In 2010, they were successful in demonstrating a 2.5 Gbps full duplex link over 130 km. This bandwidth and distance was achieved with the laser at half power [15].

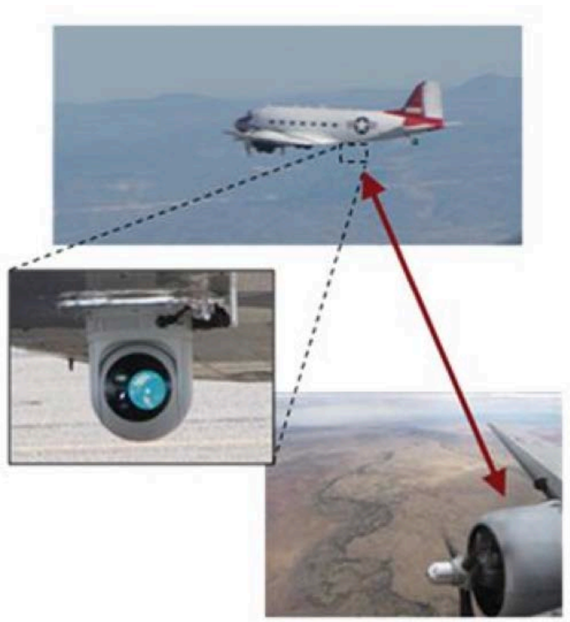

Figure 4. DC-3 Flying with FALCON communications optical node, from [15].

Work is also being done to explore the feasibility of utilizing FSO in space communications. On October 18, 2013, NASA's Lunar Laser Communication Demonstration (LLCD) transmitted data via IR energy at a download rate of 622 Mb/s and an upload rate of 20 Mb/s with a 0.5 Watt powered laser [16]. The link was roughly 238,000 miles long from the moon to a ground station in New Mexico. A high-definition video was successfully transmitted to the moon and back within seconds of processing delay. This was done error-free under all conditions utilizing high-rate pulse-position modulation and powerful error correcting codes [16, 17]. An LLCD ground terminal is shown in Figure 5.

Figure 5. NASA LLCD ground terminal, from [17].

B. ADVANTAGES AND DISADVANTAGES OF FSO COMMUNICATIONS

When comparing FSO to RF communications it is important to remember that they are two separate technologies that present their own unique advantages and disadvantages. When designing a communication system the designer must consider a number of criteria namely:

- Cost
- Bandwidth
- Availability
- Security Requirements
- Operating Environment

After taking these factors into consideration, the designer can use the appropriate level and type of technology that will satisfactorily meet the requirements. Recently, hybrid FSO and RF systems have been implemented increasing overall link performance in unfavorable atmospheric conditions. This is discussed more in later sections. In this section the focus is on the advantages and disadvantages of standalone FSO communication systems.

1. Bandwidth

Bandwidth is the measure of how much data a link can transport, usually presented in the form of bits per second. Perhaps one of the most appealing aspects of FSO is its ability to provide a very high bandwidth. The high frequency spectrum of light allows for a fast modulation rate that translates into bandwidth superior to that of most technologies operating in the RF spectrum. Most commercially available systems are capable of full-duplex bandwidths around 1 Gbps and speeds up to 2.5 Gbps are becoming more common. The current bandwidth record utilizing FSO is 1.2 Tbps. This was achieved in 2009 using wave division multiplexing (WDM) [18].

2. Spectrum Licensing

A major advantage to FSO is that it does not operate in the RF spectrum and thus its use is unregulated by government agencies such as the Federal Communications Commission (FCC). The RF spectrum is a limited resource that must be apportioned to users via a regulatory agency to ensure the deconfliction of frequencies. Consequently, this saves users the time, money and hassle of licensing a frequency spectrum with the appropriate controlling agency.

The regulation of laser use results from the requirement to ensure safe operation. There are several agencies, both internationally and domestically, that govern the standards of laser safety. Laser safety is discussed in detail in a later section.

3. Cost

FSO requires very sophisticated optical technologies for both transmitting and receiving and very precise instrumentation to successfully establish a link via the acquisition and tracking of a signal, especially in a mobile implementation. When FSO was first being seriously considered as a communication option, the technologies required for implementation were very

expensive, greatly limiting research and development. As these technologies have advanced, the cost of commercial implementation has decreased dramatically and is approaching about $1 per Gbps [19]. This is illustrated in Figure 6. Widespread consumer application and further research of the required technologies could reduce this price. Nevertheless, there is still a direct correlation between system capability and price. Systems operating over great distances, in harsh environments, and on dynamic platforms still demand a very significant budget.

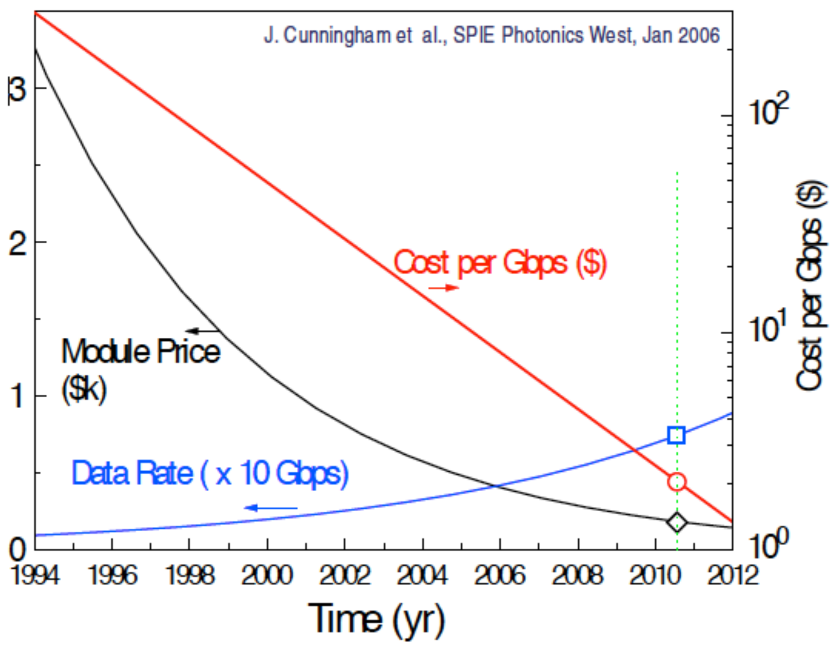

Figure 6. Module price of FSO systems and cost per Gbps versus time, from [19].

There are two major characteristics to FSO that drastically reduce cost. First, since it is a wireless technology it goes without saying that there is no need for a wired infrastructure. This is especially desirable in an urban environment, where the cost of installing the cable conveys a considerable cost, or in a military environment, where laying cable may not be tactically feasible. Second, since FSO does not operate in the RF spectrum there are no fees associated with spectrum licensing. A company called Communications Supply,

which is based in Nashville, Tennessee, advertises a 10 Gbps FSO link over a distance of 1.5 miles for $43,300 [20]. In one case, where the deployment costs of fiber were compared to the costs of FSO to service three buildings, the total came to $396,500 for fiber versus $59,000 for FSO [14].

4. Security

Another appealing aspect of FSO is its ability to be implemented as a secure communication relatively easily. Security is a major concern in nearly every form of communication. The most commonly implemented form of security is encryption. However, some communication is so sensitive that the use of encryption alone does not meet the security requirements. Communications in this category are best sent using a signal that is very difficult to detect, intercept, or exploit. Such signals are considered to have a low probability of detection (LPD), low probability of interception (LPI), and low probability of exploitation (LPE).

a. Probability of Detection

Detection is the first step in the disruption or exploitation of a communications signal. Traditional RF communications propagate a signal omnidirectionally throughout free space so that any capable receiver within range is able to detect and receive the signal. However, in FSO communications, the signal energy is directed precisely at an intended receiver. FSO communication signals can be implemented using either visible or non-visible light. The directed nature of the FSO signal by itself decreases the probability of detection. In addition, to achieve even lower probability of detection, light sources with wavelengths outside of the visible spectrum should be utilized.

In the case where visible light is implemented, detection of the signal is trivial since more likely than not the source will be visible during transmission. In some cases this may be acceptable. For example, Li-Fi is a developing technology used in place of Wi-Fi to transmit data at close range between

mobile entities such as smart phones. LED lights are optimal in this application due to their low power consumption, high eye safety qualities, the relatively short transmission distance, and the visible light as an indication to the user as to when a transmission is occurring [21].

If the detection of a signal is undesirable, FSO offers the ability to utilize energy outside of the visible light spectrum. Using the available commercial products as an indication, more often than not designers choose to work with lasers operating in the near infrared (IR) spectrum at a wavelength between 750 and 1600nm [22]. However, FSO communication research has been conducted with wavelengths encompassing the entire IR, terahertz and ultraviolet spectrums.

Operating outside of the visible light spectrum forces an adversary to rely on advanced optics equipped with the appropriate filters or sensors able to detect presence of nonvisible laser energy. Even if an adversary is in possession of the required optics, detection may still prove to be difficult or impossible depending on the capability of the optics, the characteristics of the FSO signal, the amount of particulate in the air, and the proximity to the signal. It is even more difficult to detect a signal with a sensor capable of detecting laser energy. Using such a sensor requires the user to place the sensor directly in the path of the FSO signal. This is nearly an impossible task when the location of the transmitter and receiver are unknown.

b. Probability of Intercept

The ability to intercept a communication signal implies the ability to detect and potential to exploit that signal. Therefore, having the capability to intercept data, sent either in the clear or encrypted, has very serious security implications. In order to intercept a signal an attacker must first detect that signal. If adversaries were successful in detecting an FSO signal, they would then have to position a receiver capable of demodulating the signal at the proper wavelength in a vantage point conducive to signal reception all while avoiding

detection. This would require a sophisticated attack. This attack becomes increasingly more difficult when the position of the transmitter, receiver or both is dynamic. The directed nature of the FSO signal greatly restricts the placement of an attacker's receiver. There are two feasible choices for receiver placement: in between the transmitter and receiver, or behind the receiver. If an attacker chose to place their receiver in front of the receiver they would then leave themselves susceptible to detection. The attacker's receiver would inevitably have to consistently block some of the energy intended for the friendly receiver. The friendly receiver could easily detect this drop in energy and initiate a security-defined protocol [23]. This attack is illustrated in Figure 7.

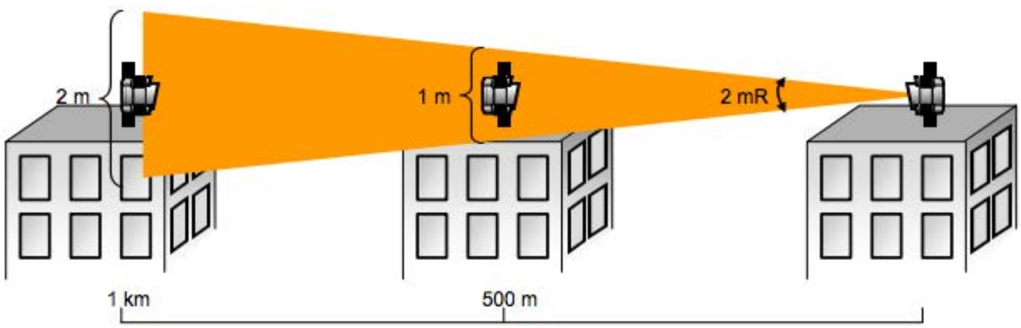

Figure 7. Interception of an FSO signal with adversary receiver placement between friendly transmitter and receiver, from [23].

Another option for an attacker would be to place their receiver behind and just offset of the intended receiver in order to capture some of the signal spillage due to beam divergence as seen in Figure 8. However, this may still require that the attacker place their receiver close to the intended recipient so that it is able to receive a useful signal. This distance is dependent on the attacker's receiver sensitivity and the transmitted signal strength. In addition, the divergence of the transmitted beam can be adjusted so that there is very little to no spillage of the signal beyond the receiver making the attacker's reception of a useful signal very difficult. Furthermore, the use of a blocking shield would

make this attack nearly impossible (see Figure 9). Ultimately, the FSO system can be designed in such a manner that the probability of intercept is very low.

Figure 8. Spillage of signal past intended receiver, from [23].

Figure 9. Blocking shield in place to prevent an adversary receiving spillage, from [23].

c. *Probability of Exploitation*

Exploitation of a signal is the drawing of useful information from the signal through decoding, location monitoring, or spoofing. Exploitation of a signal requires successful interception of the signal. Interception of the signal requires that the signal be detectable. The LPI/LPD property of FSO translates to a low probability of exploitation.

d. Denial of Service

One possible denial of service attack implemented against FSO would be jamming the signal. Since FSO is impervious to RF electromagnetic interference jamming an FSO signal can be quite difficult. The jamming of an FSO signal would require the adversary to produce energy within the view of the receiver, at the right wavelength, and at a power necessary to effectively drown out the signal sent by the transmitter. The capability exists to build a device that can produce tunable variable wavelength sources of light. Such a device could be used to conduct an attack. However, without knowledge of the signal's source it would be nearly impossible to carry out. Furthermore, the FSO transmitter and receiver could be built using a tunable energy source that would allow it to conduct a wavelength-hopping defense. The receiver's field of view can also be reduced.

5. Line of Sight

One major disadvantage of FSO is that it requires a direct line of sight (LOS) between the transmitter and the receiver. This presents a unique challenge in its implementation that is not necessarily encountered with propagated RF communications. In order to communicate between two points using FSO where an obstruction exists between the points, requires the signal to be retransmitted around the obstruction. For long distance applications of FSO the curvature of the earth becomes an obstruction increasing the difficulty of over-the-horizon implementation by essentially requiring multiple links.

6. Eye Safety

In order to responsibly operate FSO systems in an environment where a human or animal may come in contact with the beam, it is imperative to ensure that the laser is eye safe. There are currently two classification systems in use regarding laser safety ratings. The Food and Drug Administration (FDA) publishes one system, and the International Electrotechnical Commission (IEC) publishes the other in standard 60825. The systems are similar and each

defines the characteristics of the lasers in each class and the conditions under which they are considered to be eye safe. For a system to be considered truly eye safe under all conditions FSO designers are limited to the use of Class 1 and Class 1M lasers. The basics of each system classifications are detailed in Table 1 below.

<table>
<tr><th>CLASS</th><th>US: FDA/CDRH</th><th>IEC 60825
(AMENDMENT 2)</th></tr>
<tr><td>Class 1</td><td colspan="2">• No known hazards during to eye or skin during normal operation
• Note: Service Operation may require access to hazardous embedded lasers</td></tr>
<tr><td>Class 1M</td><td>N/A</td><td>• No known hazards to eye or skin, unless collecting optics are used</td></tr>
<tr><td>Class 2a</td><td>• Visible lasers not intended for viewing.
• No known hazards up to maximum exposure time of 1000 seconds</td><td>N/A</td></tr>
<tr><td>Class 2</td><td colspan="2">• Visible lasers
• No known hazard with 0.25 seconds (aversion response)</td></tr>
<tr><td>Class 2M</td><td>N/A</td><td>• No known hazard with 0.25 seconds (aversion response) unless collecting optics are used</td></tr>
<tr><td>Class 3a</td><td>• Similar to Class 2 with the exception that collecting optics cannot be used to directly view the beam
• Visible only</td><td>N/A</td></tr>
<tr><td>Class 3R</td><td>N/A</td><td>• Replaces Class 3a (with different limits)
• 5 x Class 2 limit for visible
• 5 x Class 1 limit for some invisible</td></tr>
<tr><td>Class 3B</td><td colspan="2">• Medium-powered (visible or invisible)
• Intrabeam and specular eye hazard
• Generally not a diffuse or scatter hazard
• Generally not a skin hazard</td></tr>
<tr><td>Class 4</td><td colspan="2">• High powered lasers (visible or invisible)
• Acute eye and skin hazard intrabeam, specular and scatter conditions
• Non-beam hazard (fire, toxic fumes, etc.)</td></tr>
</table>

Table 1. Description of laser classifications, from [24].

Powerful concentrated laser energy has the ability to injure both the skin and eye when contacted for a sufficiently long duration. However, specific attention is given to the subject of eye safety since generally if a laser is eye safe, then it is almost always also considered to be skin safe. The eye is more susceptible to injury from exposure to laser energy because of the ability of the eye to focus the laser energy onto the cornea. That being said, certain wavelengths are more harmful than others. Only wavelengths between 400 and 1400 nanometers are focused by the eye onto the retina [22]. The cornea absorbs other wavelengths. This absorption protects the eye from injury, unless

the energy absorbed by the cornea is sufficient enough to also cause damage. The absorption rate is higher for longer wavelengths than shorter ones. As a result, injury is more likely to occur from wavelengths in the UV and visible light spectrum than in the IR spectrum. There is also a reflex reaction that protects the eye from concentrated visible light, but this response is not triggered for wavelengths greater than 0.7µm since they are invisible [22]. Figure 10 shows how absorption varies with wavelength between 0.4 and 1.4µm.

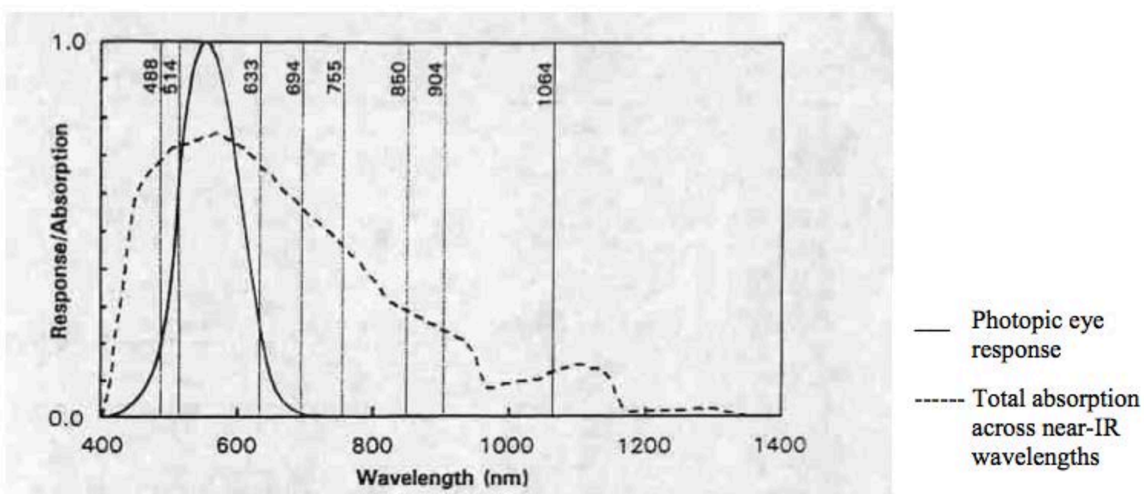

Figure 10. Absorption and photopic eye response across near-IR wavelengths, from [22].

7. Availability

Another criticism of FSO is its relatively low availability when compared to wired and RF broadband systems. Tests have shown FSO systems capable of availability of 99.9% or better at ranges from 500-1000m in cities throughout the world [22]. Table 2 will familiarize the reader with the percentage of availability and the corresponding amount of down time during a year, month and week.

Availability %	Downtime per year	Downtime per month*	Downtime per week
90% ("one nine")	36.5 days	72 hours	16.8 hours
95%	18.25 days	36 hours	8.4 hours
97%	10.96 days	21.6 hours	5.04 hours
98%	7.30 days	14.4 hours	3.36 hours
99% ("two nines")	3.65 days	7.20 hours	1.68 hours
99.5%	1.83 days	3.60 hours	50.4 minutes
99.8%	17.52 hours	86.23 minutes	20.16 minutes
99.9% ("three nines")	8.76 hours	43.8 minutes	10.1 minutes
99.95%	4.38 hours	21.56 minutes	5.04 minutes
99.99% ("four nines")	52.56 minutes	4.32 minutes	1.01 minutes
99.999% ("five nines")	5.26 minutes	25.9 seconds	6.05 seconds
99.9999% ("six nines")	31.5 seconds	2.59 seconds	0.605 seconds
99.99999% ("seven nines")	3.15 seconds	0.259 seconds	0.0605 seconds

Table 2. Availability percentage and downtime per year, month and week, from [25].

Traditionally, network availability is a function of many different factors, most particularly equipment reliability and network design, but these factors are measureable and known [22]. Obstruction of the signal is the primary cause of an FSO link outage that is unrelated to the system. This obstruction primarily is caused by particulate in the air in the form of dust, snow, rain, and fog. Equation 1 is the FSO link equation in its most basic form, omitting things such as optical efficiencies and detector noises.

$$P_{received} = P_{transmitted} * \frac{d_2^2}{\left[d_1^2 + (D*R)\right]^2} \times 10^{(-a*R/10)} \tag{1}$$

where:

P = power,

d_1 = transmit aperture diameter (m),

d_2 = receive aperture diameter (m),

D = beam divergence (mrad)

R = range (km),

a = atmospheric attenuation factor (dB/km)

Analysis of this equation shows several key characteristics of an FSO system. Focusing on the availability of the system the atmospheric attenuation variable, a, reveals that atmosphere attenuation plays a major role in system availability. Since the received power is exponentially dependent on the product of the atmospheric attenuation coefficient and the range, if a system requires 99.9% availability or better, the atmospheric attenuation dominates the equation [26]. The impacts that environmental conditions have on FSO are discussed in detail in the next section.

C. EFFECTS OF THE ENVIRONMENT ON FSO

Due to the optical nature of FSO, the performance of a system is greatly affected by the environmental conditions present between transmitter and receiver. As an FSO signal travels over a distance the signal degrades according to the amount of interference it encounters. This signal loss due to the interference experienced as the signal propagates through the atmosphere is known as atmospheric attenuation and is the result of the signal being either absorbed or scattered by several different properties of the air.

From the previous section, atmospheric attenuation will dominate all other variables of the link equation when there is a requirement for availability greater than 99.9%. The level of atmospheric attenuation will determine the performance of the FSO system. This interference comes in the form of particulates, absorption, scattering, scintillation, and turbulence. These phenomena are all products of the environment and are discussed in detail in the following sections.

It is very difficult to predict the performance of FSO systems due to the relatively unpredictable nature of atmospherics. Weather reports with the level of accuracy needed to make accurate predictions on the performance of FSO

systems are generally only collected in the proximity of airports. These reports are made public, but are limited in scope as far as area is concerned. In order to make accurate predictions of the performance of a system in a certain area it is necessary to take very accurate weather readings in the area in which the system is to be employed for an extended period of time.

1. Atmospheric Particulates

Atmospheric particulates are most commonly experienced in the form of precipitation, but are also encountered as dust, smoke, volcanic ash and other pollutants. Severe weather of all types will have a detrimental effect on performance due to the combination of dense particulate and turbulence. As one might expect, as the density of the particulate increases, the performance of the system decreases. Fog has the biggest impact on signal performance. This is due to the fact that fog is composed of water droplets that are a size optimum to interfere, through scattering, with IR wavelengths [27].

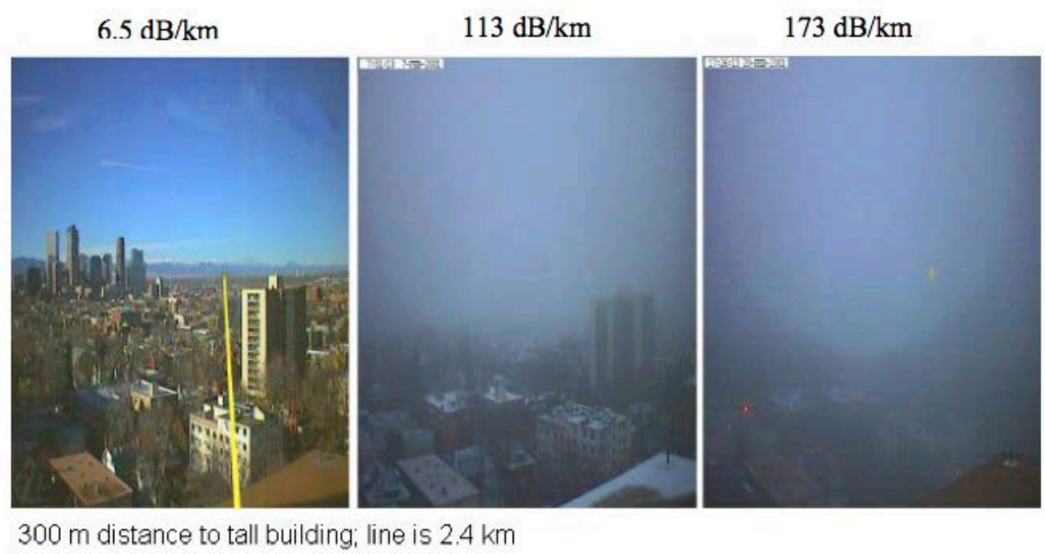

Figure 11. Fog event in Denver, Colorado, from [26].

Figure 11 depicts a fog event in Denver, Colorado, in increasing densities. The corresponding approximate attenuation is displayed above each

panel at near-IR wavelengths according to a 5% contrast standard for visibility and as defined by the World Meteorological Organization [26]. This figure illustrates that a link margin of 173 dB/km, required to operate in severe fog, and a link margin of 113 dB/km, required to operate in moderate fog, is significantly larger than the 6.5 dB/km link margin needed to operate in clear air. It is important to remember that decibels are based on a logarithmic scale of base ten. This translates to a required link margin that is roughly 10^{11} times greater in moderate fog and 10^{17} times greater in severe fog than is needed in clear air for each kilometer the signal must traverse.

2. Absorption

Absorption occurs when particles in the air weaken an optical signal by attracting part of its energy. Every type of particle that is present in the air has an absorption strength associated with it. Particles responsible for absorption can be divided into two categories: molecular absorbers and aerosol absorbers. The density and type of particles present determine the level a signal will be diminished due to absorption [27].

Water vapor is the primary molecular absorber in the near-IR wavelengths [27]. The effects of fog on an FSO signal were previously mentioned. However, this also indicates that even in clear air, a signal is attenuated based on humidity levels.

Aerosol absorbers naturally present in the atmosphere are dust, from the deserts and meteorites; sea salt particles; smoke; and volcanic ash. Aerosols are also the product of certain types of pollution. An overwhelming majority of aerosols exist over land, in the Northern Hemisphere, and within 1 km of the Earth's surface [27].

3. Scattering

Scattering occurs when the energy from a signal is refracted rather than absorbed by the particles present in the atmosphere. Scattering is most

prevalent when the radius of the particle is equivalent to the wavelength. The average radius of a fog particle is about the same size as the near-IR wavelengths most preferably used in FSO systems [27]. This is another reason why fog has such an impact on performance over precipitation with larger radii, such as rain and snow.

4. Turbulence

Turbulent air has an effect on the performance of FSO systems. Turbulence results from thermal activity and from dynamic movement of an object through the atmosphere, such as the boundary layer of turbulence that surrounds an aircraft in flight.

Turbulence affects a laser in three ways. First, the air is deflected randomly by the randomly changing particles in the air. This is known as *beam wander*. Second, it is affected by scintillation. This will be discussed thoroughly in the next section. Third, turbulence can cause the beam to diverge more than predicted [27].

Boundary layer turbulence is most commonly experienced on aircraft, but could also be a factor on fast moving ground vehicles such as bullet trains or vehicles traveling on the interstate. In the case of very high speed platforms, like a jet aircraft, as the air accelerates around the enclosure containing the FSO receiver, a transonic region develops at the tops and sides. This is a very dynamic disturbance that causes the beam to become bimodal. In the area behind the turret there is wake turbulence that causes the signal to disperse. These disturbances can be lessened by careful design of the system enclosure and its placement on the platform given proper aerodynamic consideration [28].

5. Scintillation

Atmospheric scintillation is defined as the changing of light intensities in time and space at the plane of a receiver that is detecting a signal from a transmitter located at a distance [26]. In layman’s terms, scintillation is

turbulence on a very small scale. This turbulence is the result of thermally induced changes of the air along the signal's path that results in a fluctuation of the signal at the receiver. These fluctuations cause the particles in the atmosphere to act like a series of small lenses that deflect portions of the optical signal into and out of the intended path. The time scale of these fluctuations is of the order of milliseconds, approximately equal to the time that it takes a volume of air the size of the beam to move across the path, and therefore is related to the wind speed [26]. These fluctuations are increased along a horizontal path vice a vertical one [27]. Since these changes are thermally induced the level of scintillation changes significantly throughout the course of the day. In general, scintillation levels increase as distance between transmitter and receiver increase. However, in the vacuum of space scintillation does not occur making link distances of thousands of kilometers possible [27].

Figure 12. General effect of scintillation at receiver, from [22].

Figure 12 shows the general effect of scintillation at the receiver. Scintillation causes the signal to be broken up into areas of varying intensity instead of a uniform beam of light. In the figure, the intensity scales from dark,

representing a strong speckle, to light, representing a weak speckle. This presents a problem in FSO communications because even if a receiver is capturing a single strong speckle the power of the signal will have to be increased to maintain an acceptable bit error ratio (BER) with respect to the sensitivity capability of the receiver [22].

Severe scintillation is observable as the appearance of a mirage on a hot highway or across a barren desert plain. Therefore, in FSO deployment it is recommended that the beam be at least 5 feet above possible severe sources of scintillation such as asphalt streets [27].

6. Bit Error Rate

One indication of a system's performance is the bit error rate (BER). Bit error rate, sometimes referred to as bit error ratio, is the number of received bits relative to the number of transmitted bits that have been altered over a specified length of time [29]. These alterations are attributed to noise over the signal path resulting from absorption, scattering, or interference from other sources. The bit error rate is either presented as a percentage or as a power of base ten. For example, an FSO system that reports a BER of 10^{-6} would indicate that one in one million bits delivered has been altered.

A heuristic is that as transmit power increases BER decreases. This is because BER is logarithmically correlated with the SNR. The Naval Research Laboratory has done many experiments to measure BER. Figure 13 shows some of their findings during one such experiment in 2006. The BER data were collected from a 16km one-way link for a period of five minutes at each of the power settings and then averaged.

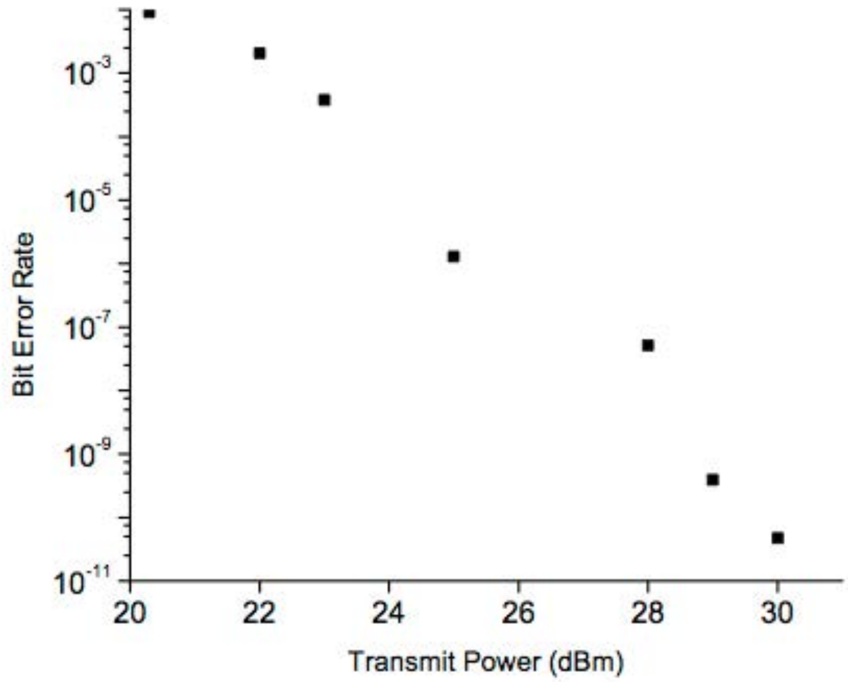

Figure 13. Avg BER versus transmit power, from [30].

Vendors of FSO systems boast the low BER of their systems and how they are capable of outperforming comparable RF systems. However, when evaluating the BER of an FSO system it is important to consider the conditions in which the measurement was taken. It is true that in order to achieve a low BER it is necessary to design a capable system. However, just like RF systems, FSO systems are at the mercy of the atmosphere they must operate in and the distance between transceivers. Therefore, it is nearly impossible to determine the actual BER of a given FSO system in a specified application until it is implemented and independent testing can be conducted.

7. Link Budget

Calculating a link budget is a good method for estimating how well an FSO system will perform. The link budget, among other things, can be used to determine how much extra power, or link margin, may be available in a link under certain operating conditions [26]. There are a number of factors that go

into the calculation of a link budget for FSO systems. At a minimum, consideration should be given to factors such as transmit power, receiver sensitivity, optical system losses, geometric losses and losses caused by pointing errors [26]. Once a link budget is calculated it can be combined with atmospheric data and distance to develop an estimate for system performance.

Transmit power and receiver sensitivity are correlated. Transmit power is a measure of the amount of energy produced by the transmitter. This can be measured at any point along the path of the transmitted beam. Receiver sensitivity is a measure of the receiver's ability to detect the transmitted energy. This is usually represented as a specific power level that corresponds to an acceptable BER. Both transmit power, and receiver sensitivity can be denoted as either peak or average power [26]. Optical system losses are those losses that occur within the system itself and those associated with scatter and absorption. Geometric losses are those that result from beam divergence. Beam divergence is the spreading of the beam from the transmitter to the receiver. The amount of beam divergence is controlled by the optics implemented in the system. Beam divergence is expressed in milliradians (mrad). One mrad equates to a spread of 1 meter at a distance of 1 kilometer.

In a perfect FSO system, it is desirable to have all the transmitted energy contained within the diameter of the receiver. In this configuration there is no geometric loss. However, this is not practical in all situations due to movement of the transmitter and receiver. Oftentimes, the system is designed so that the transmitted beam diverges to a size that is greater than the receiver. The energy that is transmitted beyond the receiver is considered geometric loss. Assuming power is uniformly distributed and there are no obscurations, geometric loss can be calculated by Equation 2.

$$\text{Geometric loss (dB)} = 10 * \log \left\{ \frac{\text{Receive Aperture Diameter (m)}}{\text{TX Aperture (m)} + [\text{Range (km)} * \text{Divergence (mrad)}]} \right\}^2 \quad (2)$$

D. FREE SPACE OPTICAL COMMUNICATION SYSTEMS

An FSO system's performance is based on two major elements: the design of the system and the atmospheric conditions within which it will operate. Of these two factors, the designer has complete control only over the design of the system. The performance of the hardware and software of a system over a given distance is predictable and can be modeled mathematically. However, atmospheric conditions are very difficult to predict accurately and are sometimes subject to unpredictable events such as fires and volcanic eruptions. This section outlines the design considerations for FSO systems and how designs can be tuned to meet operational requirements.

1. Transmitter

The transmitter operates by modulating a source of light that is typically generated by laser or light emitting diode (LED). In choosing what type of light source will be utilized the designers must consider several factors, such as the distance between transmitter and receiver, the typical expected atmospheric conditions, eye-safety, data rate, and budget.

a. Laser Types

(1) Wavelengths

Certain wavelengths are more susceptible to atmospheric attenuation than others even in ideal conditions. This is primarily due to the moisture in the air. Figure 14 shows attenuation levels for various wavelengths through clear air (visibility > 10 miles).

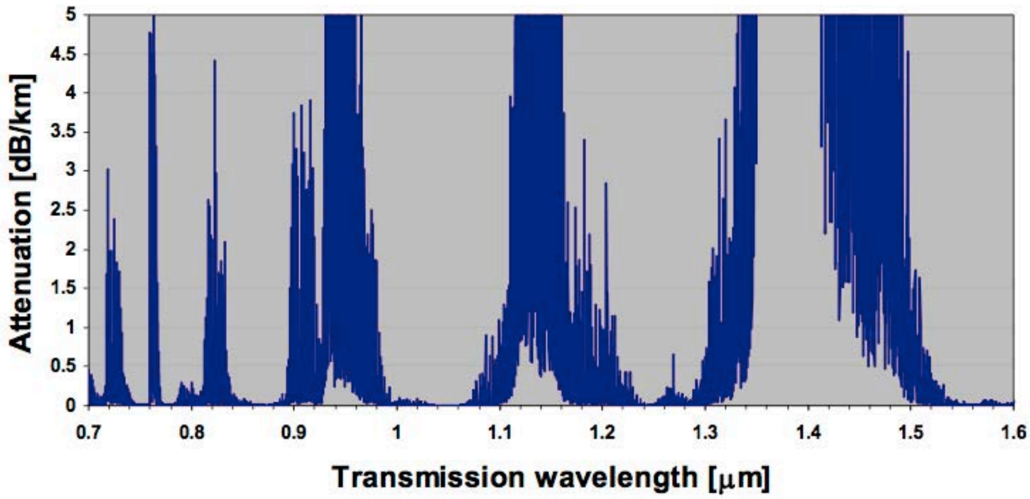

Figure 14. MODTRAN Transmission calculations under clear weather conditions, from [21].

Therefore, it is desirable to choose a laser that operates within a wavelength that has a minimal attenuation level. As a result, an overwhelming number of FSO systems are designed between 0.78-0.85 µm and 1.52-1.60 µm [26].

(2) Power

The power output available from a laser weighs heavily into the distance at which the system is capable of operating. A laser's output power is adjustable based on the power source available and is limited by a design-specified peak operating power. Operating at peak levels for an extended period of time considerably shortens the service life of the laser. Designers therefore should choose a laser that is capable of operating at an acceptable average power setting that meets distance, bit error rate, and service life requirements. Designing a system with a laser that operates at a relatively low average power setting allows the ability to increase the power during periods of high attenuation. This increase in power translates to a decreased bit error rate and improved availability. It also increases the service life of the laser. In addition, the designers can implement a coding scheme to ensure that approximately the same quantity of digital 1s as 0s are transmitted. This is

known as a 50% duty cycle. The average power setting is typically used for eye-safety classification and to define the transmit power of the transmitter [26].

2. Modulation

Modulation is the manipulation of the carrier signal to effectively transmit information. The rate at which a signal can be modulated is directly related to the wavelength of the signal. In general, shorter wavelengths (higher frequency) can be modulated at a faster rate than longer ones. In the case of FSO the signals are transmitted digitally. One of the more direct methods to modulate an FSO signal is by implementing an on-off keying (OOK) scheme. This is typically adopted in FSO applications due to the ease of implementation. In this scheme, a representative fixed power level corresponds to either a 1 or 0. However, an OOK modulation method is not necessarily the most effective modulation scheme.

Typically when considering the capacity of a communication channel in information theory Shannon’s Theorem is applied. However, researchers over the last thirty years have modeled optical links with the Poisson channel with great success. This is due to the fact that optical channels offer enormous bandwidth with relatively low noise not seen in traditional wired and wireless links [13, 31].

The capacity of an optical channel can be improved by using a modulation format with very high-bandwidth expansion ratios [32]. Figure 15 shows this phenomenon. The y-axis of Figure 15 refers to nats/photon. A nat is a unit of information based on natural logarithms vice base two logarithms used to define the bit. Nats/photon does not translate directly to bits/second. However, the graph is an excellent illustration of the previously mentioned principle since as nats/photon increases so too do bits/second.

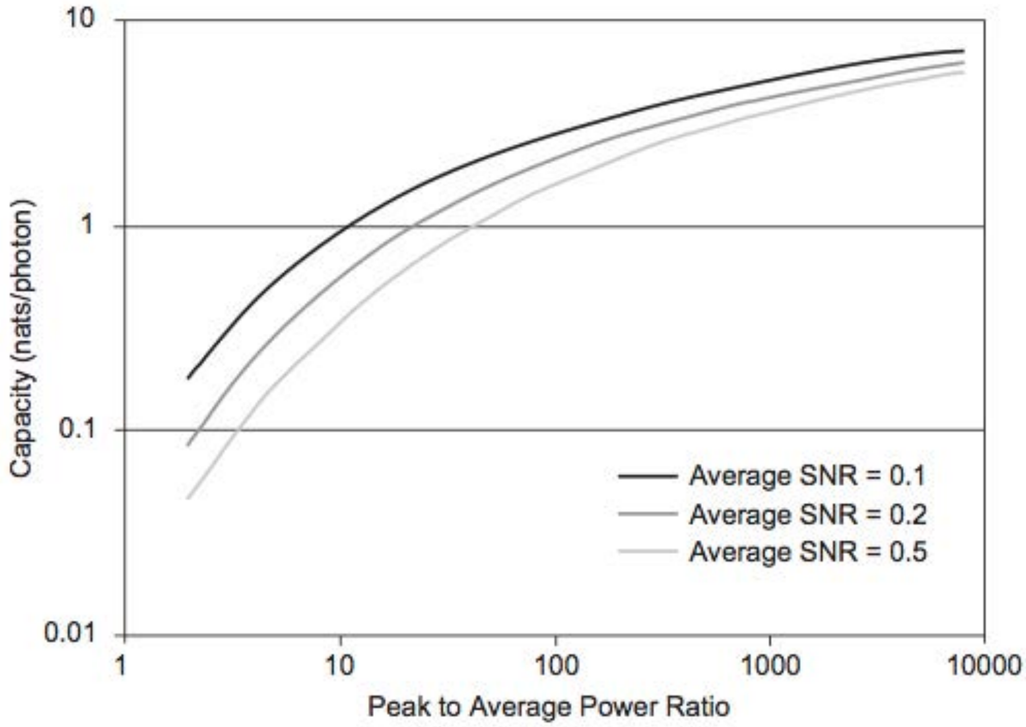

Figure 15. Channel capacity vs peak-to-average power ratio for different signal/background noise ratios, from [32].

A modulation scheme that effectively achieves a high peak-to-average-power ratio is the M-ary pulse-position modulation (PPM). In this scheme, each channel symbol period is divided into M time slots, and the information is conveyed through the channel by the time window in which the signal pulse is present. Implementing an M-ary modulation scheme allows the system to come very close to the ideal Poisson channel capacity [32]. Furthermore, this type of scheme increases the mean time between failures by limiting the amount of time the laser is operating at peak power. An example of the M-ary modulation scheme is given in Figure 16.

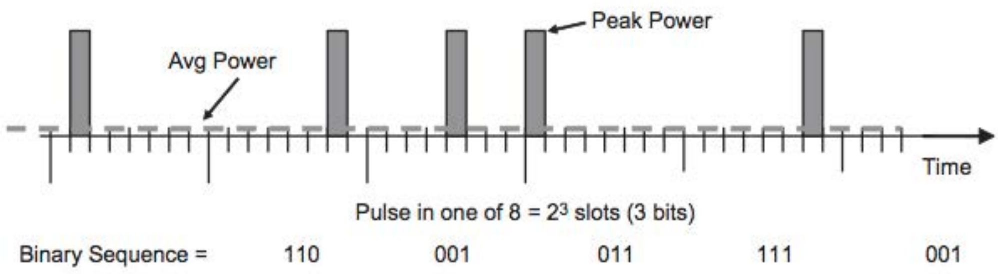

Figure 16. M-ary PPM modulation with straight binary mapping, from [32].

3. Acquisition

The acquisition of the signal must begin with a general notion of the position of the transmitter. This information can be as simple as a known fixed position or can be derived from various sources such as GPS for dynamic applications. A common method for acquisition once a general position is established is for the transmitter to send a wide-angle acquisition beam and for the receiver to scan for this acquisition beam. Once the receiver detects this beam it then sends a narrower downlink beam in the direction of the transmitter. The transmitter then detects this downlink beam, terminates scanning and sends a narrower beacon beam. Once a stable link is established the transmitter will begin sending its data via a narrow uplink beam [28]. The acquisition of a stationary (stable) signal is much more trivial than one that is mobile (dynamic). Dynamic signal acquisition must account for the relative speed and space between transmitter and receiver. However, seemingly stable applications may experience position uncertainty due to movement caused by vibration and base motion such as building sway. Figure 17 illustrates an acquisition sequence between a satellite and an aircraft.

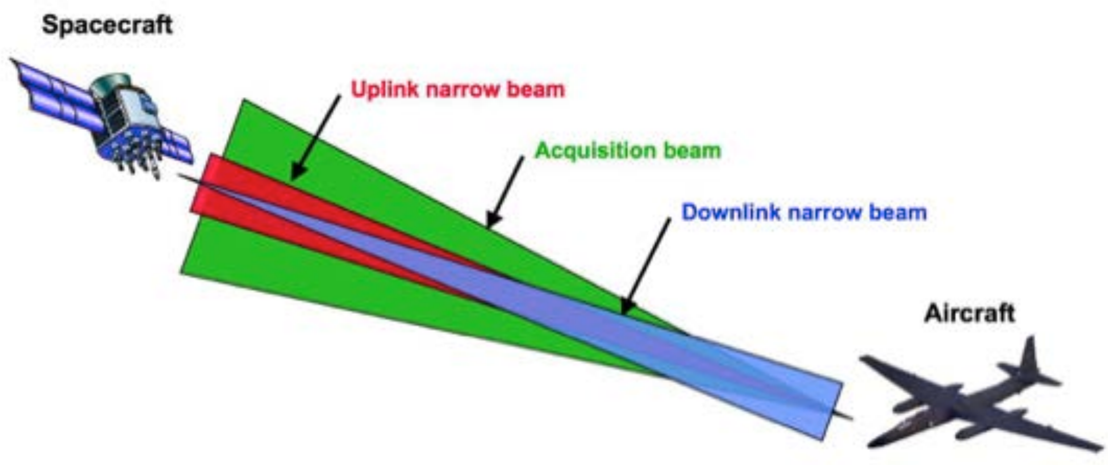

Figure 17. Illustration of beams used during acquisition, from [28].

4. Pointing

Pointing is the act of directing the beam at the intended target. In FSO, this is usually accomplished through a combination of optics, mirrors and gimbals. The gimbal is used for very coarse corrections. Steering mirrors, known as fast steering mirrors (FSM), are used to make finer corrections. This function of the FSO system relies greatly on the capabilities of the hardware and the designer's ability to take full advantage of those capabilities.

5. Tracking

Not all FSO systems incorporate a tracking capability into their design. This is due to the significant cost increase with implementing the complex hardware and software associated with tracking. For dynamic applications automatic pointing and tracking is a must. For static applications, such as those between buildings, incorporating tracking greatly increases performance by overcoming geometric losses resulting from base motion. Base motion is the inherent movement, in the form of swaying, twisting and vibration, of a seemingly fixed object. This motion may be caused by a number of factors such as wind earthquakes, or close proximity to a train track. Tracking improves performance by constantly adjusting the beams in the attempt to maintain an

optimal link. Movement of the transmitter or receiver may cause a total misalignment, causing a total loss of signal, or a partial misalignment that reduces the received power signal causing partial signal loss. Example link budgets for both tracking and non-tracking systems are provided in Figures 16 and 17. In comparison, we can see that the tracking system produces a significantly larger clear air link margin at both 300m and 2000m.

Parameter	Link Range 300 m	Link Range 2000 m	Comment
Average laser power	10.0 dBm	10.0 dBm	
System loss	–6.0 dB	–6.0 dB	Combined TX/RX terminal losses
Geometric loss	–27.0 dB	–44.0 dB	8-mrad TX divergence; 3-mrad pointing error
Signal power on detector	–23.0 dBm	–40.0 dBm	In clear air, no window loss
Detector sensitivity	–46.0 dBm	–46.0 dBm	Wavelength and data-rate dependent
Clear air link margin	23.0 dB	6.0 dB	For atmospherics and window loss

Figure 18. Link budgets for a non-tracking FSO system, from [26].

Parameter	Link Range 300 m	Link Range 2000 m	Comment
Average laser power	10.0 dBm	10.0 dBm	
System loss	–8.0 dB	–8.0 dB	Combined TX/RX terminal losses
Geometric loss	–4.0 dB	–18.0 dB	0.5-mrad TX divergence; 0.15-mrad pointing error
Signal power on detector	–2.0 dBm	–16.0 dBm	In clear air, no window loss
Detector sensitivity	–46.0 dBm	–46.0 dBm	Wavelength and data rate dependent
Clear air link margin	44.0 dB	30.0 dB	For atmospherics and window loss

Figure 19. Link budgets for an automatic tracking FSO system, from [26].

6. Overcoming Disturbances

The biggest drawback to FSO system implementation is performance degradation due to atmospheric attenuation. FSO performance is degraded by any particulate present in the air, but is most affected by particulate that tends to

hang in the air, such as haze and smoke, and less affected by particulate that occupies a space temporarily, such as rain. There are several techniques that can be implemented to mitigate losses due to atmospheric conditions. Utilizing these techniques, often simultaneously, allows designers to tailor systems to operate optimally in given locations while minimizing unnecessary costs.

a. Wavelength

Certain wavelengths perform better than others in given weather conditions. The least desirable condition is to have the diameter of the particulate to be close in size to the wavelength of the signal. Typically longer wavelengths perform better than shorter ones in heavily attenuating atmospheric conditions. However, shorter wavelengths can be modulated at faster speeds. In order to take advantage of both properties it is possible to build a system with a tunable laser. Having the ability to tune the laser allows the system to change the wavelength based on conditions to achieve an optimal signal.

b. Power

It was mentioned earlier that as power is increased BER decreases. However, transmit signal power is limited by laser capability and the power source. Also, factors such as eye safety and the laser life reliability (mean time between failures) must be carefully considered before using power as a means to improve performance.

c. Redundancy

There are several advantages to designing an FSO system with multiple transmitters and receivers. First, the chance of outage due to blockage is greatly reduced since the likelihood that all transmitters are blocked is minimal. Second, the use of multiple transmitters reduces signal degradation due to scintillation [26]. The major disadvantage to redundancy is the extra costs incurred due to additional equipment and increased system complexity.

d. Hybrid Systems

The hybrid system is a practical solution to improve system availability and performance. In a hybrid system FSO is coupled with another communication medium to achieve desired system parameters, such as bandwidth and availability. When the FSO system is not capable of meeting the system performance parameters the secondary system takes over. However, when the hybrid system reverts to RF the LPI/LPD characteristic is degraded.

E. SUMMARY

The incredible proven and potential bandwidths, rapid deployability, LPI/LPD, relative low costs, and limited licensing requirements make FSO a very appealing option for both commercial and military communications. FSO technology has advanced to the point where certain widespread uses are now possible. The commercial application of FSO between fixed points at a limited range has proven successful even in typically foggy areas such as Seattle, WA. The rapid deployment capability of FSO ad hoc networks after natural disasters and terrorist attacks make possible quick and successful reestablishment of broadband links. Space and airborne applications are currently being developed, with initial tests significantly outperforming current RF technology. There are limitations to FSO, but they are relatively few and well known. There is an ever-increasing demand for bandwidth and there is an application of FSO that can meet that demand in nearly every situation. The next chapter outlines in detail some of the different FSO systems that have been employed successfully in both commercial and experimental applications.

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III. TAXONOMY OF FSO SYSTEMS

The first part of this chapter gives the reader an understanding of FSO systems used in both commercial and experimental applications. The list of systems in this chapter is not comprehensive. However, it is substantial and accurately reflects the current state-of-the-art in FSO industry and associated technologies. The data represented in this chapter comes from the manufacturer specification sheets. The ranges and bandwidths for each chapter represent the maximum performance of the systems in ideal conditions. It is important to remember that FSO signals are degraded as atmospheric conditions degrade. Next, the reader is introduced to the Analytical Hierarchy Process (AHP) as a means of choosing an appropriate technology for a specific application. The chapter closes with an application of the AHP using FSO systems mentioned previously in the chapter.

A. STATIC FSO SYSTEMS

Static FSO transceivers are designed for use between two fixed positions, as depicted in Figure 20. This makes them ideal for enterprise and campus-like environments where buildings are fairly close together, where RF frequencies are heavily congested, and when laying cable or fiber may be too expensive or not viable otherwise. They are not capable of pointing automatically and therefore must be manually aligned carefully during installation. As a result, the signal can be lost if something knocks the link out of alignment. However, without the need for expensive gimbals and pointing software, the cost of static FSO systems is drastically less than that of dynamic systems. Automatic tracking, usually with a field of regard of just a couple degrees, is incorporated into some static systems to improve link quality by overcoming base motion. This is especially true for systems capable of transmitting over long distances.

The products in this section are available directly from the manufacturer or through third party suppliers, such as System Support Solutions based in Chaska, MN. The company's website is www.systemsupportsolutions.com.

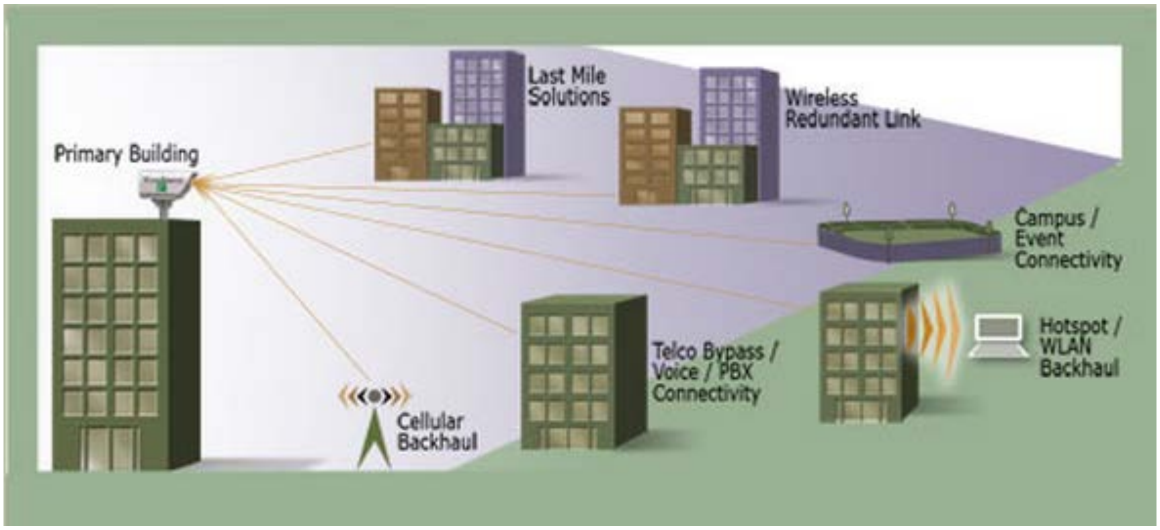

Figure 20. Typical static FSO system employment, from [33].

1. AIRLINX Communications, Inc.

The following systems are available through AIRLINX Communications, Inc. (www.airlinx.com). They are based in New Ipswich, NH. AIRLINX is an international supplier of wireless communication solutions.

a. FlightSpectrum

The FlightSpectrum system, shown in Figure 21, is the first Optical Wireless product incorporated into a major telecommunications carrier network. Due to its proven performance and price point, it has been employed in over 60 different countries. The system is capable of 40 Mbps over a range of 4 km. It incorporates a two transmitter, two-receiver configuration per unit head for increased performance [34].

Figure 21. FlightSpectrum, from [34].

b. FlightExpress 100

The FlightExpress 100, shown in Figure 22 is an entry-level product, ideally implemented as a point-to-point solution for high-bandwidth bridging delivering 100 Mbps. With a maximum range of 200 meters, the system is best for use in multi-building campus-like network environments taking the place of short optical fiber cable runs and lesser performing RF options. This system is very easily incorporated into existing LANs. System features, such as a copper interface and power-over-Ethernet, greatly simplify the installation by facilitating plug-and-play using a single CAT5 cable. The system is also very rugged and compact given its entry-level price point [35].

Figure 22. FlightExpress 100 and FlightLite series, from [35].

c. FlightStrata

The FlightStrata series incorporates auto-tracking in order to improve signal quality, especially over longer distances. The FlightStrata series builds on the multiple-beam technology of the FlightSpectrum system with transceivers utilizing a total of four transmitters and receivers providing a full-duplex signal. An automatic power control feature that prevents over saturation at the receiver allows the FlightStrata series to operate at distances as short as 1 meter. The bandwidths and ranges vary by model and are displayed in Table 3 [36].

The FlightStrata 100 XA, shown in Figure 23, is a hybrid system. It incorporates an unlicensed directional RF backup link that is capable of 72 Mbps. Combined with intelligent seamless switching between the FSO and RF links, the system achieves an availability of 99.999% in nearly all weather conditions up to 5 km. The use of multiple RF frequencies between 5.4 GHz to 5.8 GHz assures the system is compliant with frequency regulations worldwide [37].

Figure 23. FlightStrata 100 XA with flat panel RF antenna, from [37].

The FlightStrata HD was designed specifically for the streaming of high-definition video and embedded audio for HDTV. The system is capable of delivering 1.485 Gbps in order to transmit an uncompressed HDTV signal live from a camera or recorded in the field. The system is compatible with HDTV Serial Digital Interface (HD-SDI) and the transmission industry standard, SMPTE-292M [38].

Model	**Bandwidth (Mbps)**	**Max Distance (m)**
FlightStrata 52	54	5600
FlightStrata 155	155	4800
FlightStrata 622	622	3300
FlightStrata G	1250	2000
FlightStrata 100 XA	100	5000
FlightStrata HD	1485	2000

Table 3. Bandwidths and Maximum Distance for FlightStrata series, after [36-38].

d. FlightLite

The FlightLite series of FSO systems are some of the most compact systems available, weighing only 4.5 kg. Despite their compact size and lightweight, these systems are very robust and have been employed worldwide. Each system incorporates a single transmitter and receiver per unit, is full duplex, but does not have auto tracking. Table 4 details the bandwidths and maximum ranges of the FlightLite series.

FlightLite 100 and 100E are intended for use as a replacement of leased copper links between buildings. They are able to outperform RF wireless technologies, such as 802.11b, 802.11a, and 802.11g. Installation is very easy, requiring a single CAT5 cable at each end of the link [39].

The FlightLite 155 and FlightLite G systems are designed for easy fiber interface with standard subscriber connectors (SCs). These systems are ideal for high bandwidth applications such as full motion video, a high volume of Voice over Internet Phone (VoIP) connections, and large file transfer. This makes them ideal for LAN-to-LAN connectivity where laying fiber optic cable is not feasible [40].

Model	Bandwidth (Mbps)	Max Distance (m)
FlightLite 100	100	1600
FlightLite 100E	100	2900
FlightLite 155	155	2900
FlightLite G	1250	1300

Table 4. Bandwidths and Maximum Distance for FlightLite series, after [39, 40].

All of the non-hybrid systems in the Flight family are optionally upgraded to a hybrid system by incorporating the DualPath Kit. The dual path kit provides the same hybrid performance realized in FlightStrata 100 XA.

Rapid deployment of the FlightLite and FlightStrata series is made possible with Rapid Deployment Kits, shown in Figure 24. Each kit includes one transceiver, mounting hardware, power supply, and a ruggedized case.

Figure 24. Rapid Deployment Kits for FlightLite and FlightStrata, from [41].

e. UniFSO 100 and 155 Series

The UniFSO 100 series products provide 100 Mbps full duplex at a recommended range of up to 1.25 km and a maximum range of 4 km. These systems are designed to connect directly to any LAN switch, hub, or card with a 100BaseT interface without the need for any extra equipment. The systems in this series are optionally available as hybrids, incorporating a long-range directional Wi-Fi backup system increasing availability to 99.999% up to a range of 3 km. Common uses are mobile backhaul infrastructure, competitive local access networks, ISP and Wi-Fi backhaul, metropolitan video surveillance, wireless community systems and enterprise/campus systems [42].

The UniFSO 155 series is nearly identical to the UniFSO 100 series except the UniFSO system is intended for fiber interface delivering 155 Mbps full duplex. This system will connect to most fiber communication products with multi-mode or single-mode fiber optic connectors. These traits make this series

a viable last mile link option for extending IP / E1 / PDH / SDH / SONET access and networks [43]. The UniFSO 100 and 155 series transceiver unit is pictured in Figure 25.

Figure 25. UniFSO 100 and 155 series, from [42].

f. *TeraOptic 4221e*

The TeraOptic 4221e system, shown in Figure 26, provides 125 Mbps between 20 meters and 1 km. Some typical applications for this system include point-to-point wireless bridging, enterprise LAN and PBX extension, WAN connection redundancy, ISP remote Point-of-Presence, ISP direct customer connections using point-to-point, and the extension of an existing fiber network [44].

Figure 26. TeraOptic 4221e, from [44].

2. AOptix Technologies, Inc.

The following systems are developed by and available through AOptix Technologies, Inc. (http://www.aoptix.com/), based in Campbell, CA.

a. Intellimax

The Intellimax systems, shown in Figure 27, are hybrid systems combining FSO and millimeter wave technologies. There are two systems in the series: Intellimax ULL-3000 and Intellimax MB2000. Intellimax MB2000 is designed as a fiber alternative to supplement or replace fiber optic based networks. Intellimax ULL-3000 was developed to provide an FSO solution with ultra-low latency less than or equal to 1μs. Techniques such as the shortest air-path, minimizing propagation delays with a non-buffering layer one packet technology and minimizing node switching delays are implemented. Both of these systems are capable of providing 2 Gbps at a range of 10 km in all weather conditions at 99.999% availability. Installation of the systems is expedited through the use of a patented Point, Acquire, and Track (PAT) technology that quickly pinpoints and maintains the exact center of the signal, minimizing

installation costs and maximizing link margin. The systems are capable of auto-tracking within plus or minus 3 degrees from beam center [45, 46].

Figure 27. Intellimax UL3000 and MB2000, from [45].

3. Canon, Inc.

The following products are developed by and available through Canon, Inc. (www.usa.canon.com), whose American corporate headquarters are located in Melville, NY.

a. Canobeam DT-100 Series

Four models makeup the Canobeam DT-100 series of FSO systems. The Canobeam DT-100 series transceiver head is depicted in Figure 28. All of the systems incorporate automatic tracking with a maximum divergence of 1.2 degrees from center. The bandwidth and transmission distances vary by model and are displayed in Table 5. The Canobeam DT-110, DT-120 and DT-130 are designed for transmission of standard copper or fiber optic network traffic. The Canobeam DT-150 is designed for the digital transmission of both high and standard definition television formats (HD-SDI, SD-SDO, and DVB-ASI). It is able to accomplish this without compression resulting in no loss of picture quality and without any frame delay. Both the Canobeam DT-130 and DT-150

incorporate a technology that Canon refers to as 3R. This technology “Re-Shapes, Re-times, and Re-generates” to normalize the signal waveform with Gigabit class transmissions. This is done in an effort to prevent degradation of the signal where transceivers are more than 1 km apart or the LOS is compromised in some way [47].

Model	Bandwidth (Mbps)	Max Distance (m)
Canobeam DT-110	156	500
Canobeam DT-120	156	2000
Canobeam DT-130	1250	1000
Canobeam DT-150	1485	1000

Table 5. Bandwidths and Maximum Distance for Canobeam DT-100 Series, after [47].

Figure 28. Canobeam DT-100 series, from [47].

4. fSONA Systems Corp

The following products are developed by and available through fSONA Networks Corp (www.fsona.com), based in Richmond, BC, Canada.

a. SONAbeam Z series

The two products in the SONAbeam Z series were designed to provide a low-cost, lightweight, high-capacity solution for links 500m and shorter. The SONAbeam 1250-Z is able to transmit 1.25 Gbps at 500m and the SONAbeam 2500-Z provides a datarate of 2.5 Gbps over the same distance. Both systems have very low latency, are full duplex, have the ability to adjust datarates, and

carry both TDM and IP traffic on a single link by operating in a transparent mode [48].

b. SONAbeam E Series

The SONAbeam E series is a compact, rugged system ideal for rapid deployment with an available Flyaway kit. This kit includes a carbon-fiber tripod and a ruggedized, waterproof carrying case. The transceivers in this series incorporate two transmitters and a single receiver per unit for better signal quality. The E series offers full-duplex signals at varying rates and distances depending on the model employed. These values are displayed in Table 6 [49].

Model	Bandwidth (Mbps)	Max Distance (m)
SONAbeam 155-E	155	3200
SONAbeam 1250-E	1250	2700
SONAbeam 2500-E	2500	1900

Table 6. Bandwidths and Maximum Distance for SONAbeam E Series, after [49].

c. SONAbeam M Series

There are two systems in the SONAbeam M series, shown in Figure 29. The SONAbeam 155-M is capable of transmitting 155 Mbps over a distance of 5.4 km, and the SONAbeam 1250-M delivers 1.25 Gbps at a range of 4.8 km. Both of these systems utilize four transmitters and a very large receiver to achieve optimal signal quality [50].

Figure 29. SONAbeam M Series, from [50].

5. GeoDesy

The following products are developed by and available through GeoDesy Kft. (www.geodesy-fso.com), based in Budapest, Hungary.

a. PX 100 Series

There are a total of six systems in the PX 100 series offered by GeoDesy. All of the systems in this series deliver a full duplex, 100 Mbps channel ideal for Fast Ethernet connections. The range of these systems varies by model from 20 meters to 5 km. System performance can be monitored remotely via a web interface. Each transceiver in this series utilizes a single receiver and transmitter [51].

b. PX 1000 Series

In the GeoDesy PX 1000 series offers five products delivering 1000 Mbps full duplex connectivity over distances ranging from 20 meters to 3.5 km. With these systems, there is the option to couple with RF technologies for a hybrid solution. This is done via a built-in automatic failover system that is able to sense a failing link and switch before connection is lost. Furthermore, the

systems in this series have a built-in monitoring system with an LCD display at the rear of the unit [52].

c. AF Series

The Auto Focus, or AF series, is composed of three different products. Two of these systems deliver 100 Mbps. One system has a range up to 500m and the other can transmit up to 1 km. The third system delivers 1 Gbps at a range of up to 500m. All of the systems are capable of delivering a full duplex channel. They also have the self-monitoring and hybrid capabilities mentioned earlier in the PX 1000 series. The unique characteristic of this series is that beam divergence is adjustable to mitigate link degradation due to base motion. As mentioned in Chapter II, this technique is not as effective as tracking but it can be effective over short ranges [53].

d. AT Series

The Auto Tracking or AT series is comprised of the most capable systems in the GeoDesy FSO product line. Two products in the series are capable of supporting full duplex 1.25 Gbps links at ranges up to 1.2 and 2.4 km, respectively. These systems include all of the features of the other products from GeoDesy, including the option for an RF backup capable of maintaining gigabit speed while increasing overall system availability. An AT series transceiver with the optional RF backup provided by a flat panel antenna is shown in Figure 30. Unique to this series is the incorporation of automatic tracking. This technology combined, with the auto focus, offers a very effective means of maintaining link integrity [54].

Figure 30. GeoDesy FSO system with optional RF backup, from [55].

6. LightPointe Wireless

The following products are developed by LightPointe Wireless (www.lightpointe.com), based in San Diego, CA. LightPointe's products are available for purchase on a General Service Administration (GSA) Federal Schedule Contract. Contractor information can be found on the GSA website: https://www.gsaadvantage.gov/advantage/contractor/contractor_detail.do?mapName=/s/search/&cat=ADV&contractNumber=GS-35F-0609X.

a. AireLite 100, 100E and G

The AireLite 100 and 100E are capable of delivering 100 Mbps full duplex at a maximum range of 700 meters and 1 km, respectively. The AireLite G transmits 1.25 Gbps at a range of up to 600 meters. All three systems are monitored through the AireManager web-based application. These systems are very basic, as they do not offer tracking or automatic power control. However,

this simplicity makes them economical as well as ideal for rapid deployment with an available flyaway kit [56].

b. AireBridge SX

The AireBridge SX system is available in 250 Mbps, 500 Mbps, or 1000 Mbps models traversing ranges up to 1.1 kilometers. These transceivers are comprised of one transmitter and receiver. This system incorporates LightPointe’s software-defined FSO, making upgrades very easy through a software upgrade (patch). Management of the system is done through an integrated AireManager web-based control system. There is an optional hybrid upgrade available via the HyBridge 5.4/5.8 GHz unlicensed radio capable of 150 Mbps half-duplex. Radio incorporation not only increases availability but also range. The HyBridge radio increases the range of the system through a rate adaptive multiple band technology trademarked as Maximized Distance DualPath. The AireBridge SX, with optional HyBridge radio backup, is shown in Figure 31. There are several connection options to a copper or fiber infrastructure [57].

Figure 31. AireBridge SX with optional HyBridge radio, from [57].

c. AireBridge LX

The AireBridge LX system uses four transmitters and receivers per transceiver to send up to 1000 Mbps full-duplex over a maximum range of 2.5 km. Like the AireBridge SX, this system is also upgradeable to a hybrid system using the same HyBridge 5.4/5.8 GHz radio, increasing availability and range. Like the previous LightPointe systems, management is done through the AireManager system. However, this system incorporates minimal automatic tracking, to overcome base motion, as well as automatic gain control [58]. The AireBridge LX with optional HyBridge radio is shown in Figure 32.

Figure 32. AireBridge LX with optional HyBridge radio, from [58].

d. Aire X-Stream

The Aire X-Stream is very similar to the AireBridge LX in that it incorporates four transmitters and receivers per transceiver as well as automatic tracking and gain control. However, this system is capable of transmitting 1.25 Gbps over 1 km [59].

e. AireStrata G

The AireStrata G builds on the technology of the FlightStrata series. This system is identical in performance to the Aire X-Stream system previously mentioned. Unique to this system is a technology called the AirPex switch. This switch enables in-band/out-of-band management and add/drop network status indicators [56].

f. HyBridge SX and LX

The HyBridge SX and LX are radio-ready solutions allowing the user to choose a radio/frequency of their choice either at installation or later. Both models can be equipped with the HyBridge 5.4/5.8 GHz radio, providing 150 Mbps half-duplex support, as mentioned earlier, at the factory for unlicensed frequency operation worldwide. This option changes the nomenclature of the systems to the HyBridge SXR-5 and LXR-5. The HyBridge SX is capable of transmitting 1.25 Gbps over 750 meters and the HyBridge LX system is capable of 1.25 Gbps over a distance of 1.6 km. These systems include a multi-frequency adaptive-rate-modulation technology. This technology tunes system throughput based on the available system fade margin and atmospheric conditions [4, 60].

7. MOSTCOM Ltd.

The following products are developed by and available through MOSTCOM Ltd. (http://www.moctkom.ru/indexeng.htm), based in Ryazan, Russia.

a. ARTOLINK M1-FE-2A and M1-FE-L

The ARTOLINK models M1-FE-2A and M1-FE-L transmit data at a rate of 100 Mbps, full-duplex, over a range of 3 km. These two systems use a total of three transmitters and two receivers per unit. The M1-FE-L is able to extend this range to 7 km by incorporating a 5.2-5.8 GHz radio. Both systems implement automatic tracking as well as active link loss forwarding technology [61, 62].

Figure 33. ARTOLINK M1-FE-2A and M1-FE-L, from [61, 62].

b. ARTOLINK M1-GE and M1-10GE

The M1-GE transmits a maximum of 1000 Mbps full-duplex over a range of 2.5 km using an amplifier that increases the link budget by 20 dB. Otherwise, its recommended range is limited to 1.2 km. The M1-10GE is able to transmit 10 Gbps full-duplex over a range of 1.3 km. The incorporation of a 72-75 GHz millimeter wave radio increases the signal availability and range for both models. Both of these systems utilize automatic tracking and active link loss forwarding technology [63, 64].

Figure 34. ARTOLINK M1-GE and M1-10GE, from [63, 64].

8. PAV Data Systems

The following systems are manufactured by PAV Data Systems (www.pavdata.com). PAV FSO systems are available through MicroMax Computer Intelligence (http://www.micromax.com), which is based in New York. PAV data have divided their systems into two main categories: network management and corporate networks.

a. PAV Data Network Management Systems

The PAVLight has a total four models, PAVLight E1, 2xE1, 4xE1, and 4-16E1, focused on the transmission of E1 traffic. The PAVLight E1 model is designed to transmit an E1 (2.048 Mbps) data stream received through a UTP RJ45 connection. Accordingly, the 2xE1 system is designed to transmit two separate E1 traffic signals, and the 4xE1 is designed to transmit four separate E1 traffic signals. The PAVLight 4-16E1 is designed to transmit 4 to 16 E1 at 2 Mbps using G.703 protocol. However, the PAVLight 4-16E1 can also be configured as a 100 Mbps Ethernet bridge. All systems are capable of a range of 4 km utilizing three transmitters and a single receiver per unit head [65-68]. The PAVLight transceiver head is shown in Figure 35.

Figure 35. PAVLight transceiver, from [65].

b. *PAV Data Corporate Networks Systems*

There are also four models available designed specifically for corporate networking: PAVExpress 100, PAVLight 155, PAVLight 622 and the PAVLight Gigabit. The PAVExpress is an economical FSO solution for use over short ranges and does not require any equipment, such as an indoor unit, other than the transceiver. The latter three are more robust systems able to handle larger bandwidths over longer distances. These systems are capable of implementing an optional indoor unit. The indoor unit allows the system to be monitored and managed without the need to access the transceiver head. The indoor unit is pictured in Figure 36. The bandwidths and ranges are displayed in Table 7.

Model	Bandwidth (Mbps)	Max Distance (m)
PAVLight 155	155	4000
PAVLight 622/s	622	1000
PAVLight Gigabit	1000	1000
PAVExpress 100	100	200

Table 7. Bandwidths and Maximum Distance for PAV Corporate Networks Series

Figure 36. PAVLight Indoor Unit (IDU), from [69].

9. Plaintree Systems, Inc.

The following products are developed by and available through Plaintree Systems, Inc. (www.plaintree.com), based out of Arnprior, Canada.

a. WAVEBRIDGE

The WAVEBRIDGE FSO product line is made up of three series, each comprised of several systems. The LS series is designed for short-range use, the 400/500 series for midrange, and the XT series is meant for long-range applications. All three series have systems designed for Ethernet, Fast Ethernet, Clear Channel, and ATM protocols. None of the systems feature tracking to overcome base motion. Instead, beam widening is available on LS100U for applications that require some base movement mitigation. This beam widening can be adjusted to such an extreme as to accommodate several receivers from a single transmitter. As divergence of the beam increases, the range available decreases. As a result the range for the LS100U system is listed as custom as it is determined by application. A Unique characteristic of these systems is that they are based on IR LED technology instead of laser. The bandwidths and ranges of the WAVEBRIDGE systems are displayed in Table 8 [70-72]. The WAVEBRIDGE transceiver head is pictured in Figure 37.

Model	Bandwidth (Mbps)	Max Distance (m)
WAVEBRIDGE LS10	10	800
WAVEBRIDGE LS100	100	500
WAVEBRIDGE LS100U	100	custom
WAVEBRIDGE LS155	155	500
WAVEBRIDGE LS T1/E1	1 x 2.048	800
WAVEBRIDGE LS 4T1/4E1	4 x 2.048	1600
WAVEBRIDGE 410	10	1500
WAVEBRIDGE 4100	100	750
WAVEBRIDGE 4155	155	750
WAVEBRIDGE 510	10	2000
WAVEBRIDGE 5100	100	1000
WAVEBRIDGE 5155	155	1000
WAVEBRIDGE 5 T1/E1	1 x 2.048	3500
WAVEBRIDGE 5 T4/E4	4 x 2.048	2000
WAVEBRIDGE XT10	10	3000
WAVEBRIDGE XT100	100	2000
WAVEBRIDGE XT155	155	2000
WAVEBRIDGE XT T1/E1	1 x 2.048	4000
WAVEBRIDGE XT T4/E4	4 x 2.048	3000

Table 8. Bandwidths and Maximum Distance for WAVEBRIDGE systems, after [39-41].

Figure 37. WAVEBRIDGE system mounted on a tower, from [72].

10. SkyFiber Inc.

The following two products are manufactured by SkyFiber Inc. (www.skyfiber.com), based in Texas.

a. SkyLINK

The SkyLINK FSO system is able to deliver 1.25 Gbps over a range of 1.6 km. The system is made up of an optical lens unit (transceiver) and an indoor communications service terminal shown in Figure 38. Updates are expected in the near future that would increase the maximum bandwidth to 2.5 Gbps and 10 Gbps. SkyLINK Plus is a hybrid solution that has the same performance through its optical system. It is paired with a 100Mbps 802.11n backup RF signal to improve availability in unfavorable atmospheric conditions. Both systems have forward error correction [73].

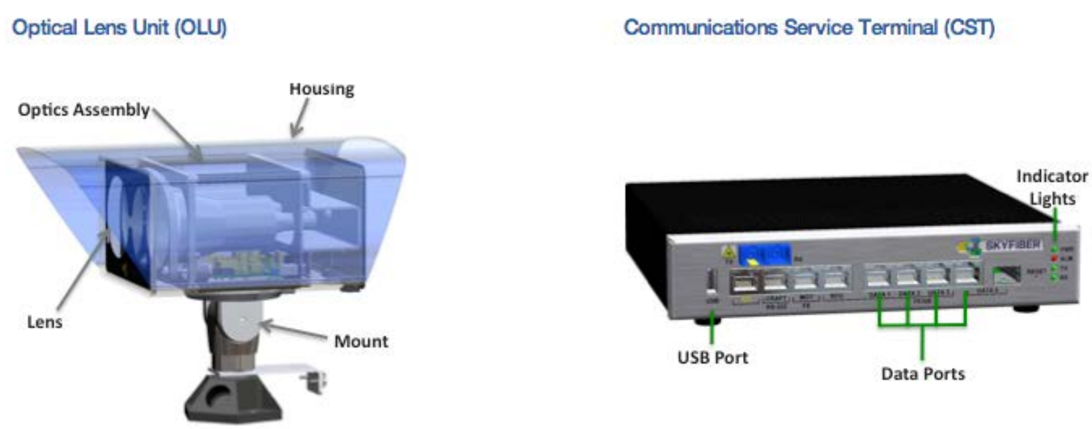

Figure 38. SkyLINK components, from [74].

11. Space Photonics Inc.

The LaserFire System is available through Space Photonics Inc. (www.spacephotonics.com), based in Fayetteville, AR.

a. LaserFire

This system is capable of transmitting 1 Gbps full-duplex over a range of 5 km. The highlight of this system, however, is the automatic Tracking, Acquisition, and Pointing (TAP) technology. This technology enables the LaserFire system to rapidly track a target, within a field of view defined by a 30-degree two-dimensional cone, without the use of gimbals or steering mirrors. The system also provides fast, continuous link-synchronization that corrects the signal for atmospheric disturbances. Setup is completed in just minutes via push-button rapid acquisition [75]. The LaserFire system is pictured in Figure 39.

Like the systems described above, the LaserFire system is a static system, not supporting on-the-move links. However, Space Photonics advertises an ability to develop custom pointing and tracking algorithms for mobile ground, airborne, and space vehicles [75]. The capabilities of this system were explored during the Joint Inter-agency Field Experimentation (JIFX) at Camp Roberts, CA, Aug. 11-14, 2014. The results of these tests are outlined in Appendix B.

Figure 39. LaserFire FSO system, from [75].

B. DYNAMIC FSO SYSTEMS

FSO systems designed for dynamic applications are by necessity more robust. The dynamic nature of one or both transceivers requires these systems to have much longer operational ranges and a more rigorous acquisition, pointing and tracking capability. To meet this demand these systems incorporate advanced software and mechanical technology such as fast steering mirrors and very precise gimbals. Furthermore, there is not a widespread demand for this type of technology as of yet. These two factors translate to a very high price point per unit. As a result, these systems are usually developed for experimental purposes with financial backing from various government organizations.

The systems are broken down into four categories: ground-to-ground, air-to-ground, air-to-air and space. Systems are categorized by proven experimental performance. However, a system may be a viable link solution in more than one category. For example, an air-to-air system may also be utilized in air-to-ground or ground-to-ground applications with sufficient modifications.

1. Ground-to-Ground Systems

Static ground-to-ground systems were discussed in detail in previous sections. This section discusses dynamic ground-to-ground systems where one or both of the transceiver's motion exceeds what would be considered standard static base motion.

a. Tactical Line-of-Sight Optical Network (TALON)

Exelis, Inc. (www.exelisinc.com) and Innovative Technology Solutions Inc. (www.nova-sol.com), commonly known as NovaSol, developed TALON. This system is capable of transmitting 100 Mbps over a distance of 50 km. TALON was developed in coordination with the Naval Research Laboratory to be able to send large amounts of data quickly from ship-to-ship and from ship-to-shore and back. The system closely resembles that of NovaSol's Compact Interrogator (CI) that was based on the earlier Dual Mode Optical Interrogator (DMOI) [2, 76]. An example of a TALON network is shown in Figure 40.

Figure 40. TALON system network diagram, from [2].

b. Compact Interrogator

NovaSol built upon their success with the DMOI by developing the smaller CI, shown in Figure 41. The CI is able to outperform the DMOI by capitalizing on advances in technology in the areas of acquisition, pointing and tracking. The CI is optionally mounted on a 25-pound gimbal that permits unattended use and stabilization on mobile platforms. The system is entirely self-contained, requiring only power, Ethernet and gimbal control connections. This system is optimized for communications with miniature modulating retroreflector (MRR) terminals. When communicating with MRRs a 10 Mbps downlink and 2 Mbps uplink is achievable. However, direct interrogator-to-interrogator (DII) links are possible for multi-Gbps transmissions [76].

Figure 41. Compact Interrogator, from [76].

2. Air-to-Ground Systems

Air-to-ground systems are designed to transfer data from a dynamic airborne platform to a static or mobile ground station. Just as in ground-to-ground systems, relative movement between the platform and ground unit varies greatly depending on distance and speed. However, in the case of air-to-ground systems the resulting relative motion is usually much greater than those contended with in ground-to-ground systems. The exception to this is high altitude air ships that may be nearly stationary depending on altitude. As a

result, there is an increase in difficulty of acquisition, pointing, and tracking. An advantage of air-to-ground links over ground-to-ground links is that it is usually easier to achieve direct LOS with an air-to-ground link due to the airborne platforms ability to maneuver above most obstacles.

a. ViaLight MLT-20 and MLT-100

ViaLight (www.vialight.de), based in Gilching, Germany, is responsible for the MLT-20 and MLT-100. Both the MLT-20 and MLT-100 are still under development, but the systems are showing promising progress. The MLT-20 is very small, weighing only 5 kg, considering it is able to transmit data at a rate greater than 1 Gbps over a maximum distance of 50 km. This makes it ideal for use not only on small aircraft, such as UAVs, but also on larger aircraft that are already weighed down considerably with numerous mission systems. Designers focused on aircraft integration concentrating on accurate pointing, low power consumption, heat dissipation, vibration resilience, and eye safety [77]. Both of these systems send location information in the form of GPS coordinates over a low-rate radio link for the purpose of acquisition. The MLT-20 is pictured in Figure 42 and a diagram of possible applications is displayed in Figure 43.

Figure 42. ViaLight MLT-20, from [77].

On December 19, 2013, ViaLight was successful in establishing a 1 Gbps link between a Tornado jet aircraft and ViaLight's Transportable Optical Ground Station (TOGS), pictured in Figure 44. The Tornado was traveling at a slant distance of approximately 60 km at a speed of 800 km/h [78]. This demonstrated distance exceeds the published maximum range of 50 km.

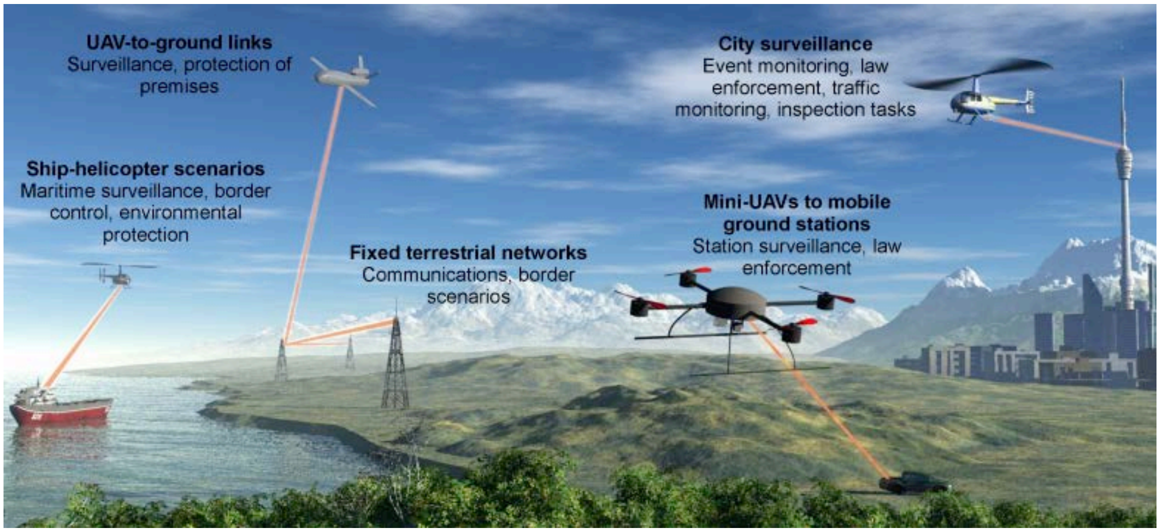

Figure 43. MLT-20 Applications, from [77].

The MLT-100 is intended for establishing high altitude backbone networks. Theoretically, the system will be capable of transmitting over 1 Gbps at a distance of 600 km. Ideally, this system will be mounted on aircraft in the stratosphere and be able to relay data received from MLT-20 terminals located below [79].

Figure 44. Tactical Optical Ground Station (TOGS), from [78].

ViaLight hopes to extend the capability of both the MLT-20 and MLT-100 so that they can also be employed as an air-to-air link solution. Tests of this nature have already been scheduled.

b. Aerostat to Ground Terminal Demonstration

In May 2006, AOptix and the John Hopkins University Applied Physics Lab demonstrated an FSO link between a tethered aerostat at an altitude of 1 km to a static ground station 1.2 km away. An experiment diagram is shown in Figure 45. Using wave division multiplexing techniques data rates of 80 Gbps were achieved. An error free transmission of 1.2 Terabits was completed in 30 seconds at a rate of 40 Gbps. In all, 30 Terabits were transferred with an average BER of 10^{-6} without the use of forward error correction coding [80]. The success of this experiment led to the decision to mount two optical links aboard the USAF Big Safari Blue Devil Block II. The Blue Devil Air Ship was to act as a host platform in the Free-Space Optical Experimental Network Experiment (FOENEX) conducted by the Defense Advanced Research Projects Agency (DARPA). However, the Blue Devil project was cancelled in June 2012 [81, 82].

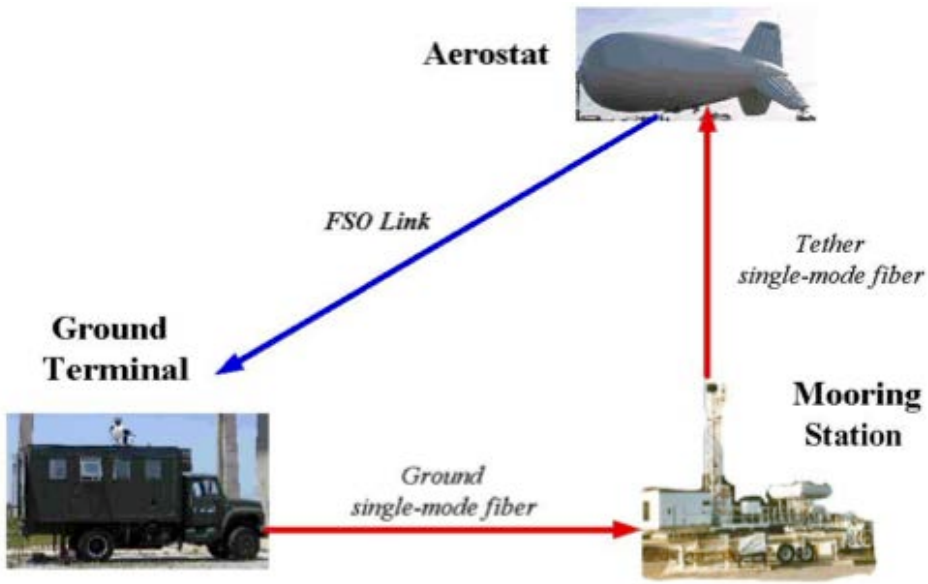

Figure 45. Aerostat to ground terminal experimental setup, from [80].

3. Air-to-Air Systems

Air-to-air systems are meant for the transfer of data from one airborne platform to another. Again, relative motion between the platforms must be overcome through acquisition, pointing and tracking systems. However, in the case of air-to-air systems this relative motion has the potential of being much more extreme, such as in the case of two very fast aircraft on converging paths, than the relative motion encountered by the previous dynamic systems. Additional factors such as aircraft vibration and boundary layer turbulence increases the challenge of transmitting and receiving a reliable optical link between airborne platforms.

a. Fast Airborne Laser Communications Optical Node (FALCON)

In 2010, FALCON successfully established a 2.5 Gbps full-duplex link between two DC-3 aircraft, at a distance of 130 km, with the laser set at nearly half power. This was the culmination of nearly a decade of research done in a partnership between the Air Force Research Lab and Exelis, Inc. This system can also be mounted on a ground vehicle [83, 84]. The FALCON

system is illustrated in Figure 4, in Chapter II, on the DC-3 aircraft and vehicle mounted in Figure 46.

Figure 46. FALCON vehicle mounted, from [83].

4. Space Systems

The vacuum of space offers an ideal operating environment for FSO since there is very little disrupting the signal. This allows for much greater transmission ranges between transceivers than what is capable within the earth's atmosphere. The challenge in space is accurately pointing and tracking the signal over a distance of tens of thousands of kilometers between two objects moving tens of thousands of kilometers per hour.

There are typically two types of communication platforms in space: low earth orbiting (LEO) satellites and geosynchronous/geostationary (GEO) satellites. LEO satellites are better for communicating with ground-based stations due to their proximity. This proximity lowers latency and improves signal quality. However, because LEO satellites are orbiting the Earth at a high rate of speed they have a relatively short transmission window and require tracking capability for both the ground station and the satellite-borne units.

Relaying a signal to a GEO satellite greatly increases transmission time and ultimately requires fewer satellites to maintain a communication link [85]. This is illustrated in Figure 47.

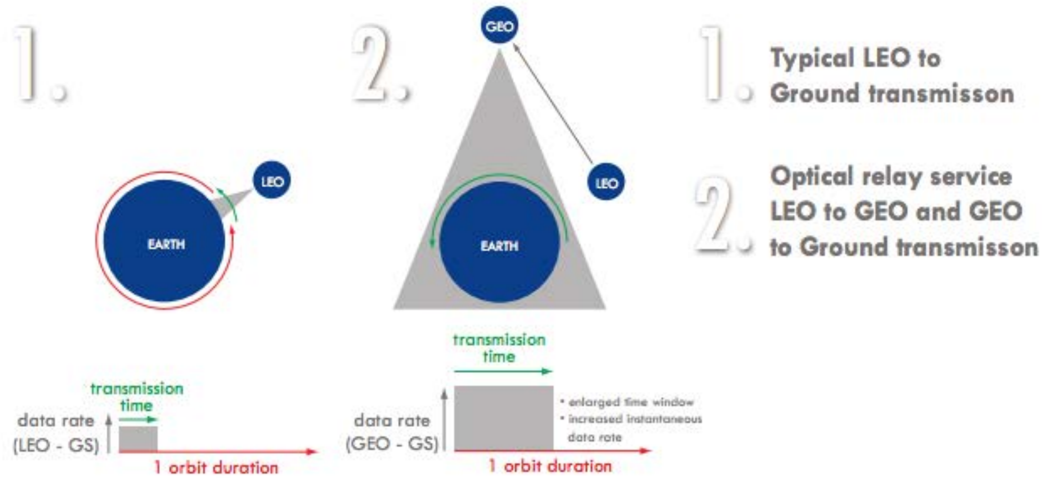

Figure 47. LEO and LEO to GEO relay transmission window and data rates, from [85].

a. *Tesat-Spacecom LCT-135*

The LCT-135 is capable of transmitting 5.65 Gbps over a distance of 45,000 km. It was developed by the German company Tesat whose website is www.tesat.de. Since 2007, the LCT-125, the predecessor to the LCT-135, has been deployed on two satellites operating in low earth orbit. This is a joint operation between the United States, and its NFIRE satellite, and the German TerraSAR-X satellite. These two satellites have transmitted data between each other on multiple occasions setting a record of 5.6 Gbps. These transmissions occur at a distance of roughly 5,000 km at a speed of 25,000 km/h over duration of 20 minutes. Tesat hopes to incorporate this system into the European Data Relay System (EDRS). Eventually, Tesat would like to incorporate high altitude air ships and UAVs into the network as seen in Figure 48 [3, 85].

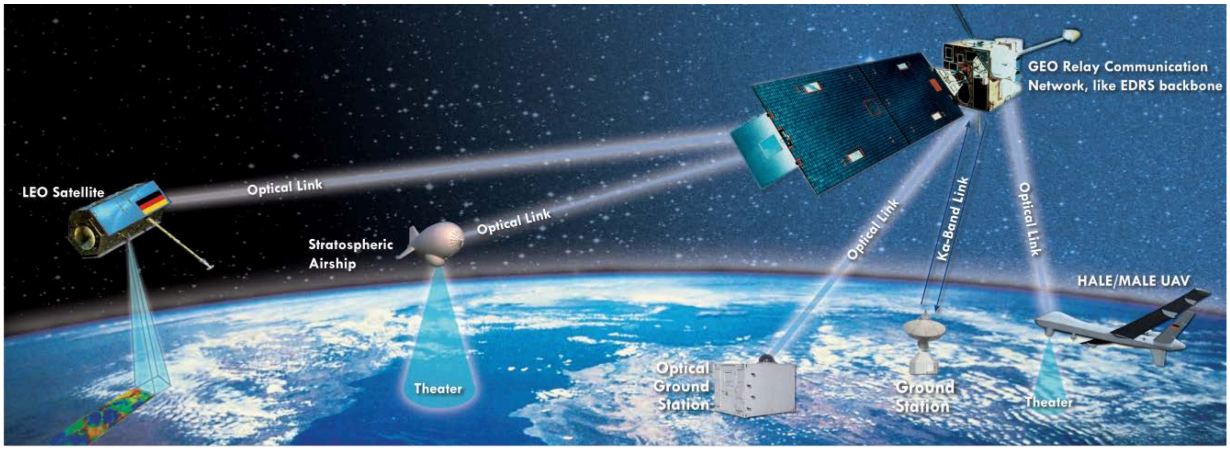

Figure 48. Space laser communication network, from [85].

b. *Ball Aerospace Laser Communication Systems*

Ball Aerospace (http://www.ballaerospace.com) is currently developing optical solutions to make a space, air, ground optical network a reality including LEO, GEO, and airborne terminals [86]. Ball Aerospace has developed the Risley Prism Beam Steering subsystems, pictured in Figure 49. These systems are able to steer and receive an optical beam over a 120-degree field of regard without the use of gimbals or turrets. This drastically reduces weight and allows the terminal to be mounted nearly flush on the aircraft reducing drag [87].

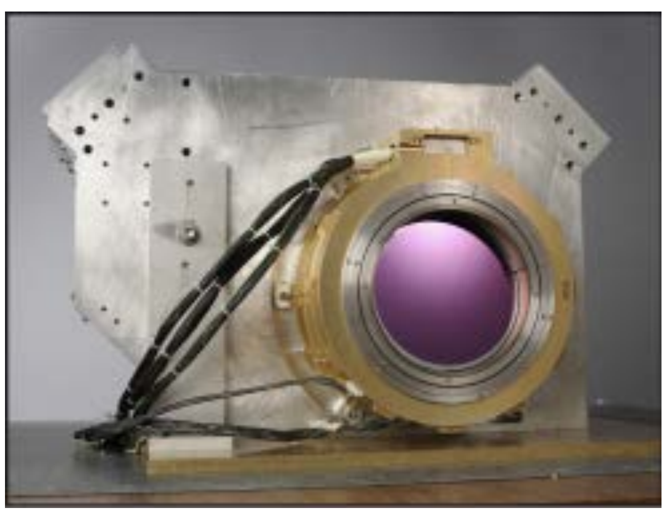

Figure 49. Risley Prism Beam Steering subsystem, from [86].

c. *Lunar Laser Communication Demonstration (LLCD)*

On October 18, 2013, NASA and the Goddard Space Flight Center's LLCD began to communicate optically from the moon at an error free rate of 622 Mbps. The link was also capable of a 20 Mbps uplink [88]. The transmissions continued for a total of thirty days. LLCD was done in conjunction with the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission. Massachusetts Institute of Technology's Lincoln Laboratory developed the LLCD ground terminal and flight system. There were a total of three ground stations, as shown in Figure 50. The European Space Agency (ESA) successfully communicated with the flight terminal from a ground station on Tenerife in the Canary Islands [17].

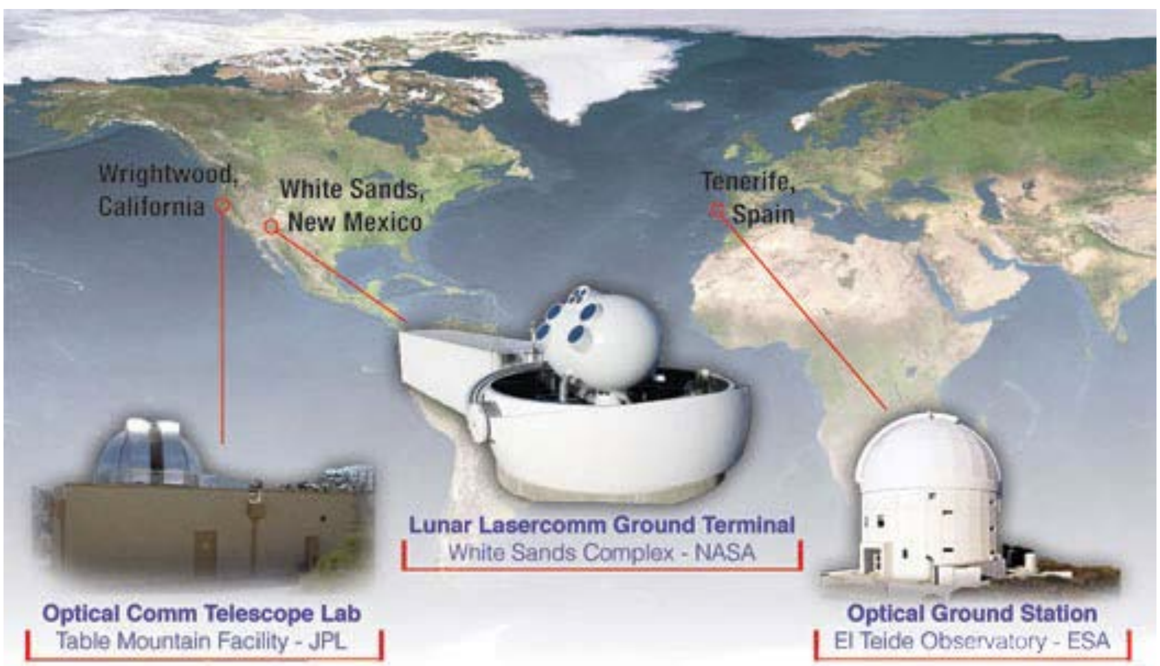

Figure 50. LLCD ground station locations, from [89].

In the previous sections of this chapter we have discussed the capabilities and limitations of current FSO communication systems. Some of these systems are available commercially allowing for possible rapid integration into the military communication construct with minor or no modifications. In the

next section, the Analytical Hierarchy Process (AHP) is discussed as a means for selecting the best system for a given application given a set of defining attributes.

C. THE ANALYTICAL HIERARCHY PROCESS (AHP)

The AHP is a mathematical tool that can be utilized to aid in making a seemingly difficult decision, such as choosing an optimal FSO system for a particular application. It was developed by Thomas L. Saaty and initially introduced in 1977. Consequently, it is sometimes referred to as the Saaty method [90]. This section provides an introduction to the AHP and a simple example of its application.

1. Basic Principles of AHP

The first step of AHP is to develop a matrix representing the relative values of a chosen set of attributes. For example, in the case of an FSO system these attributes may be something like high bandwidth or maximum range. Construction of the matrix involves asking the user to compare the importance of high bandwidth to maximum range and then assigning a particular value to their answer according to Table 9 adopted from Saaty. For instance, if high bandwidth were absolutely more important than maximum range a value of 9 would be assigned [91].

Intensity of importance	Definition	Explanation
1	Equal importance	Two factors contribute equally to the objective
3	Somewhat more important	Experience and judgement slightly favour one over the other.
5	Much more important	Experience and judgement strongly favour one over the other.
7	Very much more important	Experience and judgement very strongly favour one over the other. Its importance is demonstrated in practice.
9	Absolutely more important.	The evidence favouring one over the other is of the highest possible validity.
2,4,6,8	Intermediate values	When compromise is needed

Table 9. The Saaty Rating Scale, from [91].

Since the user has claimed that high bandwidth is absolutely more important than maximum range, then maximum range must be assumed absolutely less important than bandwidth. Due to this reciprocal relationship a value of 1/9 is where maximum range is absolutely less important than bandwidth. The matrix is complete when all pairwise comparisons are complete. For simplicity sake, great effort should be given to try and minimize the number of comparisons in each matrix. This can usually be accomplished by ensuring that contributing attributes do not overlap [91].

Several matrices are developed in the AHP, one for the attributes themselves, and one for the products being compared and each individual attribute. Once each of the matrices has been filled in, an eigenvector is calculated for each. This basically entails calculating a list of the relative importance of each the attributes being considered for the first matrix, and how well the products are able to meet each attribute for the subsequent matrices [91].

Once an eigenvector has been calculated for each matrix, a final matrix is completed displaying the results of the process. A step-by-step example of AHP is given later in this chapter comparing FSO systems previously discussed.

2. Capabilities and Limitations of AHP

There are some advantages and disadvantages associated with the AHP. One of the most appealing aspects of the AHP is its ability to effectively rank choices in order of their ability to meet conflicting objectives. Another, attractive quality of the AHP is that if the matrices are populated with as accurate assessments as possible then the results of the AHP are very accurate. Thus, it is very difficult to manipulate the data in order for the AHP to reveal a predetermined result. Yet another feature of the AHP that adds to its value is its ability to identify inconsistencies in the initial judgments [91].

The mathematics behind the AHP is based on the positive reciprocal matrix. This means if a value of 9 is chosen to represent one aspect as absolutely more important than another, a value of 1/9 must be assigned to the relationship of the latter to the former. There are some who find this a drawback. Furthermore, changing the scale to something other than 1-9 will change the final numerical result. However, this may not represent in a change of the actual result since the result is relative. For example, a final result of (0.220, 0.398, 0.403) representing products X, Y, Z means that Y and Z are a better choice than X, but they are not two times better [91].

D. AHP EXAMPLE

This section provides an example of the AHP derived from [92]. This is a very basic example intended as an introduction to the AHP and what it can provide. In actual practice, more detail may be applied. Implementation of AHP in this example was completed using Microsoft Excel. This is an ideal method for implementation since it allows to user to run multiple iterations using different values very easily. Furthermore, the mathematics of the AHP will not be discussed. There are several ways to calculate the eigenvector. The basics of the mathematical computations involved can be found in [91, 92].

The goal of this example is to select an FSO system that is capable of a dynamic application. Additionally, four systems and five attributes will be

considered. This information is organized in the hierarchical tree shown in Figure 51.

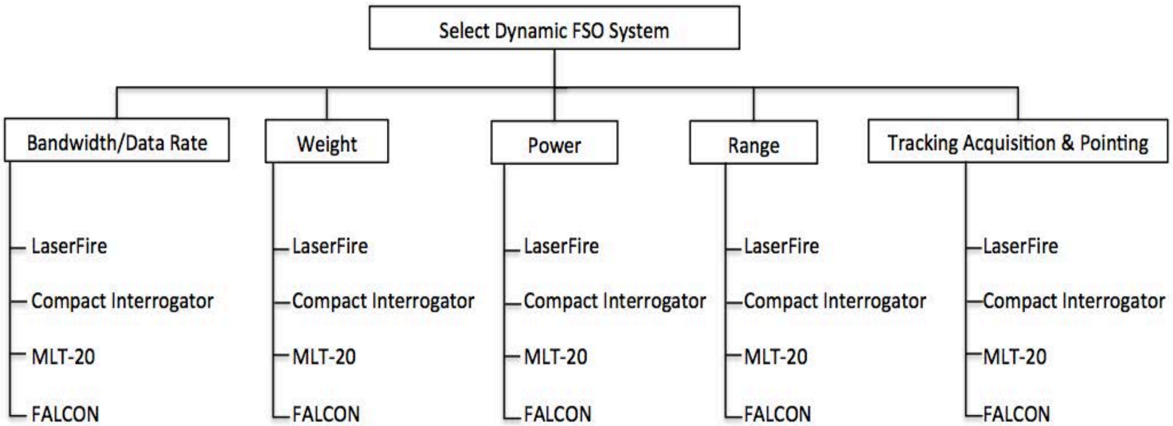

Figure 51. AHP information in hierarchical tree.

Next, the pairwise comparisons are completed arbitrarily for the sake of the example using the scale in Table 9, yielding the matrix shown in Table 10.

Prioritization Matrix	Bandwidth/Data Rate	Weight	Power	Range	TAP	EV
Bandwidth/Data Rate	1	9	5	3	0.2	0.304
Weight	0.111	1	0.333	0.142	0.2	0.033
Power	0.2	3	1	0.333	0.2	0.068
Range	0.333	7	3	1	2	0.259
Tracking Acquisition & Pointing (TAP)	5	5	5	0.5	1	0.336

Table 10. AHP prioritization matrix.

Computing the eigenvector for this prioritization matrix reveals the result shown in the last column of Table 10 (highlighted yellow). From this result, bandwidth and TAP are nearly equally important, range is the next most important factor, and weight and power have little importance compared to the other attributes.

Now, matrices for each attribute are completed and their respective eigenvectors computed (shown in green) representing each system's ability to satisfy the attribute. These matrices are displayed in Tables 11 through 15.

Bandwidth/Data Rate	LaserFire	Compact Interrogator	MLT-20	FALCON	EV
LaserFire	1	0.2	1	0.143	0.081
Compact Interrogator	5	1	3	0.5	0.317
MLT-20	1	0.333	1	0.333	0.115
FALCON	7	2	3	1	0.487

Table 11. Bandwidth matrix and associated eigenvector.

According to this result, FALCONs 2.5 Gbps data rate makes it the best choice as far as bandwidth is concerned.

Weight	LaserFire	Compact Interrogator	MLT-20	FALCON	EV
LaserFire	1	7	0.5	5	0.330
Compact Interrogator	0.143	1	0.125	2	0.075
MLT-20	2	8	1	8	0.539
FALCON	0.2	0.5	0.125	1	0.056

Table 12. Weight matrix and associated eigenvector.

From this result, at only 5 kg, the MLT-20 is the best choice where weight is concerned.

Power	LaserFire	Compact Interrogator	MLT-20	FALCON	EV
LaserFire	1	7	5	5	0.582
Compact Interrogator	0.143	1	0.125	2	0.093
MLT-20	0.2	8	1	2	0.241
FALCON	0.2	0.5	0.5	1	0.084

Table 13. Power matrix and associated eigenvector.

Here it is observed that the LaserFire's 20W maximum power consumption makes it the most energy-friendly option.

Range	LaserFire	Compact Interrogator	MLT-20	FALCON	EV
LaserFire	1	0.2	0.2	0.111	0.045
Compact Interrogator	5	1	1	0.2	0.165
MLT-20	5	1	1	0.2	0.165
FALCON	9	5	5	1	0.625

Table 14. Range matrix and associated eigenvector.

The FALCON's 130 km range makes it the most evident choice by a considerable margin where range is concerned.

Tracking Acquisition & Pointing (TAP)	LaserFire	Compact Interrogator	MLT-20	FALCON	EV
LaserFire	1	0.333	0.2	0.143	0.059
Compact Interrogator	3	1	0.333	0.25	0.133
MLT-20	5	3	1	0.5	0.305
FALCON	7	4	2	1	0.503

Table 15. TAP matrix and associated eigenvector.

The FALCON system also dominates the TAP matrix.

Now the results from each of the attribute matrices are multiplied with their corresponding values in the prioritization matrix. These values are summed for each system to determine the systems final score.

The final results are shown in tabular form in Table 16 and as a spider graph in Figure 52. This spider graph has five axes each representing one of the five attributes. For each system a plot is placed along the axis corresponding to the system's eigenvector for that particular attribute. These plots are then connected with a different colored line representing each system. The area encompassed by one of these lines gives a nice graphical representation of what system is the best choice and how far off the other systems are. A larger area corresponds to a better choice. This graph also allows for a quick comparison of each individual attribute with the plots farthest from the origin representing the most favored system for a particular attribute.

From our example we see that the FALCON system, with a score of 0.486, is the best choice, followed by the MLT-20, then the Compact Interrogator, and finally the LaserFire.

Summary	Bandwidth/Data Rate		Weight		Power		Range		Tracking Acquisition & Pointi		
	Weighting	Score	Weighting	Score	Weighting	Score	Weighting	Score	Weighting	Score	**Final Score**
LaserFire	0.304	0.081	0.033	0.330	0.068	0.582	0.259	0.045	0.336	0.059	0.107
Compact Interrogator	0.304	0.317	0.033	0.075	0.068	0.093	0.259	0.165	0.336	0.133	0.193
MLT-20	0.304	0.115	0.033	0.539	0.068	0.241	0.259	0.165	0.336	0.305	0.214
FALCON	0.304	0.487	0.033	0.056	0.068	0.084	0.259	0.625	0.336	0.503	0.486

Table 16. Final results of AHP example.

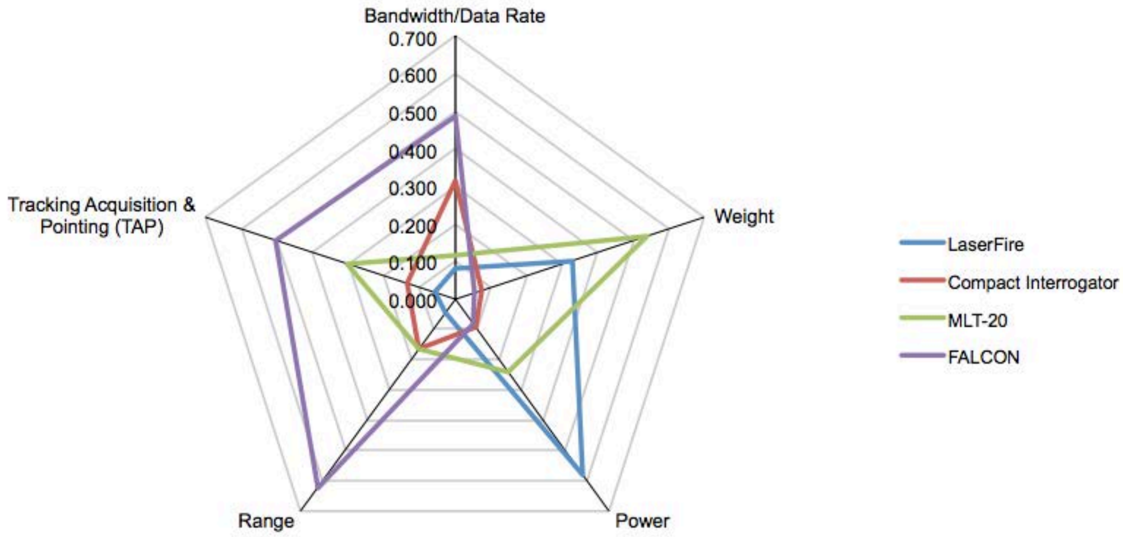

Figure 52. Final results of AHP example.

E. SUMMARY

This chapter provided the reader with an understanding of state of FSO systems as well as an idea of their performance under ideal conditions. Both commercially available systems and those still going through the research and development process were discussed. In Chapter IV, an analysis of how these systems could be implemented in the military environment is conducted.

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IV. SUITABILITY ANALYSIS OF FSO SYSTEMS IN THE MILITARY ENVIRONMENT

This chapter analyzes the suitability of FSO systems in the military environment. When discussing the military environment there are two factors that must be considered. First, there is the combat or tactical environment. Combat operations have unique communication requirements that are not necessarily directly translated from the civilian sector due to the need to operate in remote locations under very harsh conditions. Second, there is the administrative environment. The administrative environment would correlate to a major military installation that has access to a robust communication backbone like fiber optic cable. The military administrative environment's communication requirements, in many cases, translate directly from the civilian environment. The vast majority of the military operates in the administrative environment. Nevertheless, it can quickly change to the combat environment in the event of an attack. This chapter considers these requirements and weighs whether or not FSO is a viable option. This chapter analyzes each of the categories that were used to classify the dynamic FSO systems in the taxonomy presented in Chapter II.

A. GROUND-TO-GROUND

Ground-to-ground FSO links can either be static, where both ends of the link are fixed, or dynamic where one or both links are capable of being operated while mobile. An example of a static ground-to-ground link in the military environment would be a link between a higher and lower headquarters COC. An example of a dynamic ground-to-ground link would be an operational link between two moving tactical vehicles such as A1 Abrams tanks.

1. Static

Static ground-to-ground FSO has been implemented with resounding success worldwide in the civilian sector and can be a very viable option for the

military. These systems are designed for establishing networks for enterprise and campus like environments. Military bases fit into this category. There is a significant demand for broadband network connectivity on and between military installations both domestically and abroad in both tactical and non-tactical environments. Of all the available FSO systems, static systems have been in production the longest and have proven performance records. These systems can be installed quickly and cheaply without expending the labor to lay cable or place personnel in harm's way. Furthermore, they are available as a commercial off the shelf (COTS) technology that can be acquired through the General Services Administration (GSA) for immediate deployment.

a. Intra-Base Networking

Intra-Base networking, or networking within the base, would be a direct translation of FSO technology from the civilian sector to the military for non-tactical applications. Most of the buildings on military installations are in fairly close proximity to another building, well within the range of capable FSO systems. Tactical applications, such as networking a remote Forward Operations Base (FOB) or Patrol Base (PB) may require more ruggedized equipment. However, this could be achieved through minor modifications to the COTS equipment. It should not be the intent to set up a network between all of the buildings on an installation, but to incorporate FSO in areas where there is a demand for fiber-like broadband connectivity and laying fiber optic cable is not viable due to operational constraints, cost, or safety to personnel. Furthermore, an FSO-RF hybrid solution with a sufficient tracking capability should be used to ensure maximum link performance and availability in all atmospheric conditions and periods of increased base motion caused by heavy vehicle and aircraft traffic as well as shockwaves from exploding ordnance.

The high demand for broadband connectivity within COCs was discussed in Chapter I, and FSO would be able to meet that need. However, another area where there is an extremely high demand for broadband connectivity within

military installations is on the networks provided by Morale, Welfare, and Recreation (MWR). When deployed, military personnel rely very heavily on Internet connectivity for communication and entertainment purposes. As a result it is not uncommon for Internet café's to be established by MWR on remote FOBs and for the larger bases to provide installation-wide Wi-Fi access. These networks are stressed heavily by service members conducting video and voice calls, downloading content, and streaming video. Low bandwidth makes call quality poor, and stresses the service members trying to communicate with friends and family. Incorporating FSO into these networks would improve their performance.

b. Inter-Base Networking

Inter-Base networking, or networking between installations, presents a greater challenge due to the increased link distance requirements. In the case of non-tactical military installations there is a high likelihood of access to the fiber infrastructure negating the need for FSO inter-Base networking. However, tactical military installations are unlikely to have access to a secure wired infrastructure. Therefore, they must be connected by wireless means. Tactical military installations are usually placed within a proximity to other tactical military installations so that they can mutually support one another in the case of an overwhelming enemy attack. This usually translates to a few kilometers or even less in high threat environments. Again, this is well within the range of capable commercial FSO systems. For longer distance requirements, systems such as TALON, with a max range of 50 km [2], would prove effective. However, as distance increases obstacles may become an issue when trying to establish LOS between FSO units. Techniques such as elevating the unit and communication relay may be used to increase range and mitigate LOS issues as long as such techniques are tactically feasible.

c. Communication Relay Stations

FSO systems would also be a viable option for static ground-based communication relay stations. However, consideration should be given to the relatively fragile nature of an FSO link due to poor atmospherics and the LOS requirements. A hybrid solution, which incorporates FSO and RF communications, would probably be most viable in the case of communications relay. This would afford the station the bandwidth and security benefits of FSO communications in favorable conditions and the availability of RF communications otherwise.

d. Hastily Formed Networks

The ability to rapidly establish and reestablish communications is paramount in military operations. FSO and FSO-hybrid systems have the ability to setup high bandwidth links extremely quickly via the "fly away" kits discussed in Chapter II. They are capable of doing so without interfering with RF communications through the use of IR energy and unlicensed radio frequencies. This is ideal for reestablishing communications in a disaster relief or post attack situation where the communication architecture has been damaged or destroyed. This capability has already been proven in the civilian sector following the terrorist attacks on the World Trade Center in 2001 [13].

2. Dynamic

FSO would prove very beneficial in ship-to-ship and ship-to-shore communications. This was demonstrated using the TALON system [2]. The likelihood that LOS between two ships on the open ocean, or the LOS between a ship at sea and a shore-based communications station is blocked is minimal assuming proper maneuver coordination. Increasing the number of ships potentially would allow for a more robust network, again assuming proper coordination. Without proper coordination, the likelihood of link blockage grows as the number of ships in the area increases and as the communication station

is moved further inland. Some of the challenges encountered in establishing FSO links on surface ships can be found in [93].

For nearly every other tactical or administrative communication scenario a dynamic ground-to-ground FSO communication link is not suitable, except in applications that would require very short transmission ranges. This is simply due to the LOS requirement. Establishing and maintaining LOS over the ground dynamically would be difficult, if not impossible, especially in a tactical scenario where cover and concealment is required. Currently, most tactical ground communications are done over VHF frequencies vice UHF frequencies for this very reason. VHF frequencies are better able to mitigate obstacles between communication nodes. UHF is primarily used for air-to-ground and air-to-air communications due to its ability to transmit over longer distances with a better quality signal. However, UHF requires LOS. From personal experience, UHF frequencies have nowhere near the LOS requirements of FSO. With UHF, it is possible to establish a communication link from a covered position, such as under a tree or inside a building, to an aircraft. With FSO this would not be possible. Nevertheless, UHF is still considered unsuitable for ground-to-ground communications.

B. AIR-TO-GROUND

An air-to-ground FSO link is one established between an airborne platform and either a static or dynamic ground station. An example of air to a static ground link would be the FMV from a UAV transmitted back to a COC or to the UAVs static control center. An example of an air to dynamic ground FSO link would be a UAV transmitting its FMV feedback to a moving vehicle or foot mobile combat troop.

1. Dynamic Air to Static Ground

An FSO link from an airborne platform down to a static ground station may prove beneficial in both military and civilian communications. LOS is easily obtainable from an airborne platform as long as that platform has the ability to fly

at an altitude that can support an adequate look angle from the ground station to the airborne platform, and as long as the ground station transceiver is able to be exposed for signal transmission and reception. This is almost always achievable with highflying fixed-wing aircraft and high-altitude airships. However, lower flying rotary-winged aircraft and smaller UAVs may not be able to establish and maintain continuous LOS due to tactical necessity or aircraft limitations. This might be acceptable in certain communication scenarios as long as the link can be quickly reestablished. ViaLight successfully demonstrated this application of FSO with its MLT-20 system from a Tornado fighter jet [78]. John Hopkins University Applied Physics Lab and AOptix also demonstrated this capability by establishing an 80 Gbps link between a tethered aerostat and a ground terminal [80].

2. Dynamic Air to Dynamic Ground

The suitability of an FSO communications link from an airborne platform to a dynamic ground station is marginal. This is again due to the LOS requirement. Whether the ground station is vehicle-mounted or man-portable there is a very high likelihood that the movement of the ground station will inevitably find it in a position where an obstacle, man-made or natural, will interrupt the LOS between it and the airborne platform. A hybrid solution might work for this scenario, but size, weight, and power must be carefully considered especially for man-portable ground transceivers. For this reason, RF systems such as the GhostLink are a more viable option for tactical scenarios.

The GhostLink system, shown in Figure 53, is a high-bandwidth RF solution for air-to-dynamic-ground links currently being developed by General Atomics Aeronautical Systems Inc.

Figure 53. GhostLink, from [94].

According to [94], the GhostLink is an LPI/LPD airborne data link capable of transmitting 80 Mbps over a range of 180 km. The system uses proprietary Ultra-wideband (UWB) technology that allows the transmission of FMV from an airborne ISR platform, such as a UAV, to a tactically employed ground operator for real-time situational awareness.

C. AIR TO AIR

An air-to-air FSO link is one established between two airborne platforms. The capabilities of airborne platforms vary greatly in payload capacity and flight profiles. This variety in platform allows for great flexibility in application. For example, FSO links could be established between small UAVs operating at relatively low altitudes, between two tethered aerostats, or between an aircraft and a high altitude airship (HAA). The AFRL demonstrated this capability with the FALCON system [83].

a. High Altitude

High altitude air-to-air FSO links show very high potential. The biggest detractor to an FSO link is the LOS requirement and the atmosphere the link energy must travel through. Placing FSO transceivers on platforms very high in the atmosphere affords the link the possibility of operating in an environment where the air is less dense. This “thin air” translates to the capability of transmitting over longer distances since there is less in the air to interfere with the link. Additionally, there is far less air traffic at high altitudes to potentially momentarily block the link resulting in data loss. However, LOS will eventually become a limiting factor due to the curvature of the Earth. Furthermore, high altitude air platforms tend to be very stable with very long loiter times.

b. Low Altitude

Low altitude air-to-air FSO links are also promising. However, lower altitudes present several challenges to FSO links due to higher air density and a closer proximity to the ground. This correlates to more particulate present in the atmosphere at that can interfere with the FSO link quality and limit range. FSO links on low flying air platforms are more likely to experience link blockage from natural or manmade obstacles. However, if the FSO link is directed upwards from the low flying air platform to a higher flying or space platform a great deal of these challenges may be mitigated. The exception to this is the low flying platform operating below a layer of clouds. However, since FSO performs poorly in fog, it might not be possible for the FSO link to penetrate the cloud layer in this case [95].

Inter-base networking might be one possible use for a low altitude air-to-air FSO link. The Persistent Threat Detection System (PTDS), pictured in Figure 54, is used extensively as an ISR platform on FOBs.

Figure 54. Persistent Threat Detection System (PTDS), from [96].

The PTDS may serve as the ideal platform for inter-base networking for a two reasons. First, it is a tethered aerostat. This means that it has an extremely long loiter time and is a relatively stable platform. Second, it is capable of operating at hundreds of feet above the ground. This may help mitigate the degrading effects of dust and scintillation. It may also aid in establishing LOS between two FOBs. One drawback to the PTDS as an FSO platform is that the system does have wind limitations that may hinder its ability to remain airborne.

D. SPACE

The vacuum of space provides the perfect operating environment for FSO. Without interference from the atmosphere, FSO is able to reliably transmit high data rates over very great distances making them ideal for deep space communications. Space links can be established between two space vehicles, or from a space vehicle back to a terminal within the Earth's atmosphere. The successes of the LLCD and the Tesat satellite systems have demonstrated this incredible capability [3, 17]. A major drawback to space systems is the need to

put them into space to be tested at these extreme distances. This is very costly and usually needs to be supported by government to achieve the funding required.

E. GLOBAL NETWORK

FSO will play a very valuable role in establishing global networks such as the European Data Relay System (EDRS) [3, 85]. Using FSO to establish links between high altitude airborne platforms and space vehicles will provide a bandwidth and security capability not available through RF communications. Again, careful consideration must be given to where exactly FSO links will be implemented in these networks to ensure the highest level of availability given bandwidths and RF spectrum constraints.

F. SUMMARY

This chapter provided an analysis of FSO systems in the military environment. FSO has very promising qualities that might prove very valuable for the military. Tactical applications of FSO are limited due to the LOS requirements. However, the range capabilities at high altitudes and in space make it very valuable for establishing global networks and for deep space communications. The next chapter provides a summary of the thesis, conclusion and recommendations, and suggestions for future work.

V. SUMMARY, CONCLUSION AND RECOMMENDATIONS

A. SUMMARY

This research surveyed the current state of FSO communications and then analyzed its suitability for application in the military operating environment. This was completed by first providing a thorough background of FSO to provide an understanding of their capabilities and limitations. Next, a systematic survey of current FSO systems relevant to military communications was completed. From this survey, a matrix of system capabilities and limitations was populated for ease of reference. Then the Analytical Hierarchy Process (AHP) was introduced, as a means of choosing an appropriate system, and an example was given of its application. Next, an experiment was conducted using two systems, establishing two separate links simultaneously to gain hands on experience and an understanding of realistic performance expectations. Finally, a suitability analysis of FSO was completed for communication scenarios typical to the military operating environment.

The military has an ever-increasing demand for bandwidth in a very RF dense operating environment. The ability for FSO communications to securely transmit very large data rates impervious to RF energy makes it very appealing as a possible military communication solution.

B. CONCLUSION

FSO communication is a viable solution for certain military applications. There are undeniable performance advantages of FSO over RF communications for certain scenarios under certain conditions. The modulated light of FSO is capable of supporting much larger bandwidths than RF frequencies. The collimated laser energy of FSO provides LPI and LPD qualities making it very resistant to exploitation. FSO’s immunity to RF interference makes the signal resilient to jamming and allows operation without frequency deconfliction. These benefits are significant for military

communications where a great deal of money is spent on equipment and software and effort expended securing RF communications usually resulting in degraded link performance. However, there are also considerable limitations to FSO that prevent it from being a direct replacement for all RF communication links. These limitations are atmospheric interference, a strict LOS requirement and a limited ability to conduct area transmissions.

The performance of an FSO link is directly correlated to the atmospheric conditions within which it is operating. Particulates in the air, turbulence and air density all impact FSO link performance. For this reason, it is difficult to accurately determine how FSO will perform in a given environment over time until it can actually be tested in that environment for an appropriate period of time. This is also true for RF communications, but the effect that atmospherics have on FSO is much greater than on RF. This is very concerning when considering FSO as a communication solution where high-availability in all weather conditions is a priority. Implementing a hybrid FSO-RF solution can mitigate link degradation in unfavorable atmospherics. However, in doing so the LPI/LPD and RF immunity of the link is compromised. Additionally, there are several possible applications of FSO where adverse atmospherics will most likely not be encountered. These include space applications, high altitude air-to-air links and on UAVs that are only capable of operating in visual meteorological conditions (VMC) due to ISR sensor and/or aircraft limitations.

The requirement for LOS is the biggest limitation to FSO because it will simply not operate without it. Establishing LOS in tactical situations can be difficult and dangerous as it usually involves elevating and exposing the transceiver, the operator or both. Due to the LOS limitation, FSO systems are most suitable for static ground-to-ground, static ground-to-air, air-to-air and space applications. The LOS requirement makes FSO unsuitable for dynamic ground-to-ground and marginal for dynamic ground-to-air links, except in applications that only require very short transmission ranges. There are merely too many obstacles encountered between two moving ground stations and

between a moving ground station and an airborne platform. The exceptions to this are FSO links between surface ships, between a surface ship and an airborne platform and for ship-to-shore communications. The open sea provides a relatively obstacle free environment across its surface. However, links over the ocean eventually fall victim to the LOS requirement due to the curvature of the Earth.

The collimated laser energy used in FSO communications aids in the security of the link through LPI and LPD, but is not effective in disseminating information to multiple receivers. The only way to transmit, from a single transmitter, over an area is by increasing beam divergence. As beam divergence increases, the range of the link decreases. Currently, FSO is not suitable for applications requiring the dissemination of information to multiple dislocated nodes from a single source.

C. RECOMMENDATIONS

Research in the area of FSO communications should continue to be aggressively pursued. The bandwidth, security, and RF immunity qualities of FSO communications present too many benefits to communications in the military environment to be ignored. This research should focus on better understanding the capabilities of current systems, improving the performance of FSO in adverse atmospheric conditions, and exploring new applications of FSO systems in the military communications construct.

D. FUTURE WORK

1. Modulating Retro-reflectors (MRR)

The Naval Research Laboratory (NRL) has been conducting research on FSO since 1998. Some of their recent work has been in the area of modulating retro-reflectors (MRR). One of the current limitations to a standard dynamic FSO link is that a turret/gimbal is required at both ends of the link. This adds considerable complexity to the design and increases the cost, size, weight and

power (CSWaP) requirements of the systems. An MRR, pictured in Figure 55, is very small and alleviates CSWaP requirements for one end of the FSO link [97].

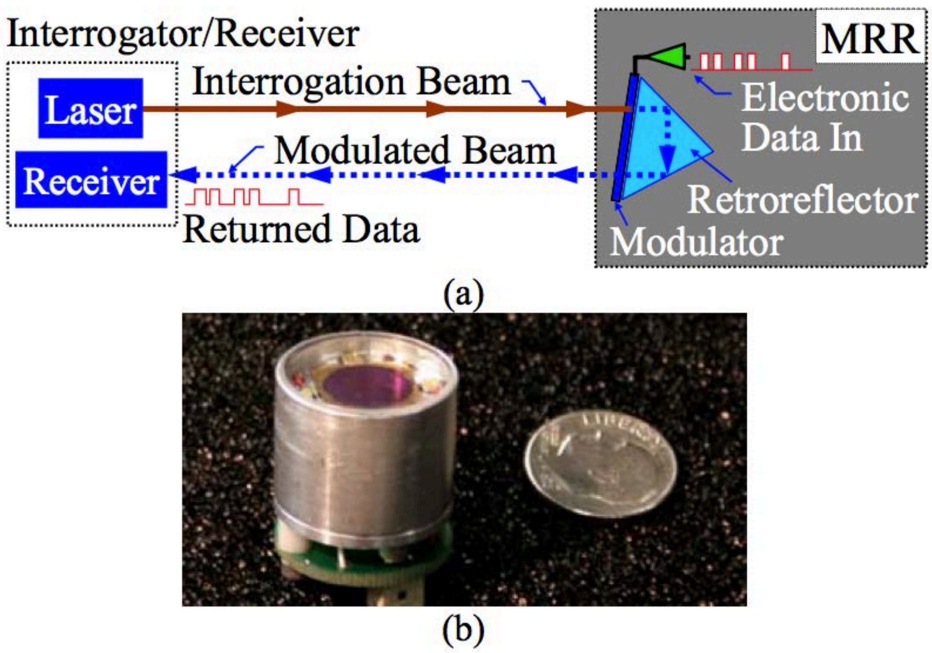

Figure 55. A (a) MRR system diagram and (b) MRR transmitter, from [97].

This is potentially a very valuable application of FSO technology, especially in airborne applications where CSWaP requirements tend to be more stringent. The NRL's work on MRRs has been published in [97]. The Command, Control, Communications, and Intelligence Division of the Australian Defence Science and Technology Organisation expanded on the work done by the NRL. That work can be found in [98]. Future work with MRRs should focus on the following areas:

(1) Validate interrogation of an airborne MRR by a ground-based FSO system.

(2) Validate the ability of an airborne MRR to simultaneously modulate two independent interrogation signals from two dislocated ground based FSO systems.

(3) Validate the ability of an airborne MRR to demodulate data received from one FSO ground station while simultaneously modulating data to another dislocated FSO ground station.

(4) Develop and validate an air-to-air FSO link incorporating MRR technology with the goal of reducing CSWaP requirements for the airborne FSO system.

2. Other Future Work

Other future work general to FSO and not directly related to MRR implementation might involve:

(1) Conduct a thorough AHP to select a suitable hybrid FSO-RF system or systems for the intra-Base application considering the following criteria:

- Bandwidth
- Range
- Ambient operational temperatures
- Performance in all atmospheric conditions
- Cost, Size, Weight and Power (CSWaP)
- Resistance to base motion caused by vehicle/aircraft traffic and ordnance shock wave

(2) Validate performance of hybrid FSO-RF systems selected by AHP through independent experimentation.

(3) Demonstrate encrypted FSO transmissions.

(4) Develop a magnetic torque steering system for FSO systems that would improve a system's pointing, acquisition and tracking capability.

(5) Continue to seek out, acquire and validate the performance of FSO communication systems for military communications.

(6) Conduct a study to insure IR covert lighting used on tactical military aircraft does not interfere with FSO signal transmissions.

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APPENDIX A. FSO SYSTEM SPECIFICATION MATRIX

A.1 STATIC FSO SYSTEMS

FSO System Name	*Max Bandwidth (Mbps)*	*Max Oper Dist (m)*	Weight (kg)	*Max Pwr Cons (W)*	Hybrid	Pointing	Tracking	Min Op Temp(C)	Max Op Temp (C)	Contact
FlightSpectrum	40	4000	13.5	20	optional	manual	none	-25	60	AIRLINX Communications, Inc.
FlightStrata 52	54	5600	11.1	40	optional	manual	auto	-25	60	AIRLINX Communications, Inc.
FlightStrata 155	155	4800	11.1	40	optional	manual	auto	-25	60	AIRLINX Communications, Inc.
FlightStrata 622	622	3300	11.1	40	optional	manual	auto	-25	60	AIRLINX Communications, Inc.
FlightStrata G	1250	2000	11.1	40	optional	manual	auto	-25	60	AIRLINX Communications, Inc.
FlightStrata 100 XA	100	5000	20	40	yes	manual	auto	-20	60	AIRLINX Communications, Inc.
FlightStrata HD	1485	2000	11.1	40	optional	manual	auto	-25	60	AIRLINX Communications, Inc.
FlightExpress 100	100	200	4	15	optional	manual	none	-30	60	AIRLINX Communications, Inc.
FlightLite 100	100	1600	4.5	15	optional	manual	none	-30	65	AIRLINX Communications, Inc.
FlightLite 100E	100	2900	4.5	15	optional	manual	none	-30	65	AIRLINX Communications, Inc.
FlightLite 155	155	2900	4.5	20	optional	manual	none	-25	60	AIRLINX Communications, Inc.
FlightLite G	1250	1300	4.5	20	optional	manual	none	-25	60	AIRLINX Communications, Inc.
UniFSO100 Series 400A	100	250	15	NA	optional	manual	none	-40	70	AIRLINX Communications, Inc.
UniFSO100 Series 400B	100	400	15	NA	optional	manual	none	-40	70	AIRLINX Communications, Inc.
UniFSO100 Series 500	100	600	15	NA	optional	manual	none	-40	70	AIRLINX Communications, Inc.
UniFSO100 Series 700	100	900	15	NA	optional	manual	none	-40	70	AIRLINX Communications, Inc.
UniFSO100 series 1000B	100	1250	15	NA	optional	manual	none	-40	70	AIRLINX Communications, Inc.
UniFSO155	155	250	15	NA	optional	manual	none	-40	70	AIRLINX

series 400A										Communications, Inc.
UniFSO155 series 400B	155	400	15	NA	optional	manual	none	-40	70	AIRLINX Communications, Inc.
UniFSO155 series 500	155	600	15	NA	optional	manual	none	-40	70	AIRLINX Communications, Inc.
UniFSO155 series 700	155	900	15	NA	optional	manual	none	-40	70	AIRLINX Communications, Inc.
UniFSO155 series 1000B	155	1250	15	NA	optional	manual	none	-40	70	AIRLINX Communications, Inc.
TeraOptic 4221e	125	1000	9.3	60	no	manual	none	NA	NA	AIRLINX Communications, Inc.
Intellimax ULL-3000	2000	10000	82	80	yes	auto	auto	-40	55	AOptix Technologies Inc.
Intellimax MB200	2000	10000	82	80	yes	auto	auto	-40	55	AOptix Technologies Inc.
Canobeam DT-110	156	500	8	20	no	manual	auto	-20	50	Canon Inc.
Canobeam DT-120	156	2000	8	20	no	manual	auto	-20	50	Canon Inc.
Canobeam DT-130	1250	1000	8	20	no	manual	auto	-20	50	Canon Inc.
Canobeam DT-150	1485	1000	8	20	no	manual	auto	-20	50	Canon Inc.
SONAbeam 155-E	155	3200	10	40	no	manual	none	-40	60	fSONA Networks Corp
SONAbeam 1250-E	1250	2700	10	40	no	manual	none	-40	60	fSONA Networks Corp
SONAbeam 2500-E	2500	1900	10	40	no	manual	none	-40	60	fSONA Networks Corp
SONAbeam 155-M	155	5400	20	60	no	manual	none	-40	60	fSONA Networks Corp
SONAbeam 1250-M	1250	4800	20	60	no	manual	none	-40	60	fSONA Networks Corp
SONAbeam 1250-Z	1250	500	10	25	no	manual	none	-40	60	fSONA Networks Corp
SONAbeam 2500-Z	2500	500	10	25	no	manual	none	-40	60	fSONA Networks Corp
PX 100 Series PX-P0200E100TP	100	200	25	50	no	manual	none	-40	60	GeoDesy
PX 100 Series PX-P0350E100TP	100	350	25	50	no	manual	none	-40	60	GeoDesy
PX 100 Series PX-P0650E100TP	100	650	25	50	no	manual	none	-40	60	GeoDesy

PX 100 Series PX-P1800E100TP	100	1800	25	50	no	manual	none	-40	60	GeoDesy
PX 100 Series PX-P3000E100TP	100	3000	25	50	no	manual	none	-40	60	GeoDesy
PX 100 Series GD-5000E100TP	100	5000	25	50	no	manual	none	-40	60	GeoDesy
PX 1000 Series PXW-P0400E1000TP	1000	400	25	50	optional	manual	none	-40	60	GeoDesy
PX 1000 Series PXW-P0650E1000TP	1000	600	25	50	optional	manual	none	-40	60	GeoDesy
PX 1000 Series PXW-P1000E1000TP	1000	1000	25	50	optional	manual	none	-40	60	GeoDesy
PX 1000 Series PXW-P1400E1000TP	1000	1400	25	50	optional	manual	none	-40	60	GeoDesy
PX 1000 Series PXW-P3500E1000TP	1000	3500	25	50	optional	manual	none	-40	60	GeoDesy
AF Series PX-P0500E100/AF/TP	100	500	15	50	optional	manual	none	-40	60	GeoDesy
AF Series PX-P1000E100/AF/TP	100	1000	15	50	optional	manual	none	-40	60	GeoDesy
AF Series PX-P0500E1000TP/AF/TP	1000	500	15	50	optional	manual	none	-40	60	GeoDesy
AT Series AT-P1200E1000TP	1250	1200	25	50	optional	manual	auto	-40	60	GeoDesy
AT Series ATW-P2400E1000TP	1250	2400	25	50	optional	manual	auto	-40	60	GeoDesy
AireLite 100	100	700	4.5	20	no	manual	none	-30	60	LightPointe Wireless
AireLite 100E	100	1000	4.5	20	no	manual	none	-30	60	LightPointe Wireless
AireLite G	1250	600	4.5	20	no	manual	none	-30	60	LightPointe Wireless
AireBridge SX	1000	1100	4.5	20	optional	manual	none	-30	60	LightPointe Wireless
AireBridge LX	1000	2500	15	40	optional	manual	auto	-25	60	LightPointe Wireless
Aire X-Stream	1250	1000	15	40	no	manual	auto	-25	60	LightPointe Wireless

AireStrata G	1250	1000	15	40	no	manual	auto	-25	60	LightPointe Wireless
HyBridge SX	1250	750	15	40	optional	manual	none	-30	60	LightPointe Wireless
HyBridge SXR-5	1250	750	15	40	yes	manual	none	-30	60	LightPointe Wireless
HyBridge LX	1250	1600	15	40	optional	manual	auto	-25	60	LightPointe Wireless
HyBridge LXR-5	1250	1600	15	40	yes	manual	auto	-25	60	LightPointe Wireless
FSO ARTOLINK model M1-FE-2A	100	3000	14	20	no	manual	auto	-40	50	MOSTCOM Ltd
FSO ARTOLINK model M1-FE-L	1000	7000	14	20	optional	manual	auto	-40	50	MOSTCOM Ltd
FSO ARTOLINK model M1-GE	1000	2500	13	45	optional	manual	auto	-40	60	MOSTCOM Ltd
FSO ARTOLINK model M1-10GE	10000	1300	8	20	optional	manual	auto	-40	50	MOSTCOM Ltd
PAVLight E1	2.048	4000	14.9	30	no	manual	NA	-40	65	PAV
PAVLight 2 x E1	2 x 2.048	4000	14.9	30	no	manual	NA	-40	65	PAV
PAVLight 4 x E1	4 x 2.048	4000	14.9	30	no	manual	NA	-40	65	PAV
PAVLight 4 - 16E1	100	4000	14.9	15	no	manual	NA	-40	65	PAV
PAVLight 155	155	4000	14.9	15	no	manual	NA	-40	65	PAV
PAVLight 622/s	622	1000	14.9	15	no	manual	NA	-40	65	PAV
PAVLight Gigabit	1000	1000	14.9	15	no	manual	NA	-40	65	PAV
PAVExpress 100	100	200	4	30	no	manual	NA	-40	65	PAV
WAVEBRIDGE LS10	10	800	3.2	NA	no	manual	none	-40	70	Plaintree
WAVEBRIDGE LS100	100	500	3.2	NA	no	manual	none	-40	70	Plaintree
WAVEBRIDGE LS100U	100	custom	3.2	NA	no	manual	none	-40	70	Plaintree
WAVEBRIDGE LS155	155	500	3.2	NA	no	manual	none	-40	70	Plaintree
WAVEBRIDGE LS T1/E1	1 x 2.048	800	3.2	NA	no	manual	none	-40	70	Plaintree
WAVEBRIDGE LS 4T1/4E1	4 x 2.048	1600	3.2	NA	no	manual	none	-40	70	Plaintree
WAVEBRIDGE 410	10	1500	9	NA	no	manual	none	-40	70	Plaintree
WAVEBRIDGE 4100	100	750	9	NA	no	manual	none	-40	70	Plaintree
WAVEBRIDGE 4155	155	750	9	NA	no	manual	none	-40	70	Plaintree
WAVEBRIDGE 510	10	2000	9	NA	no	manual	none	-40	70	Plaintree
WAVEBRIDGE 5100	100	1000	9	NA	no	manual	none	-40	70	Plaintree
WAVEBRIDGE 5155	155	1000	9	NA	no	manual	none	-40	70	Plaintree
WAVEBRIDGE 5 T1/E1	1 x 2.048	3500	9	NA	no	manual	none	-40	70	Plaintree

WAVEBRIDGE 5 T4/E4	4 x 2.048	2000	9	NA	no	manual	none	-40	70	Plaintree
WAVEBRIDGE XT10	10	3000	15	NA	no	manual	none	-40	70	Plaintree
WAVEBRIDGE XT100	100	2000	15	NA	no	manual	none	-40	70	Plaintree
WAVEBRIDGE XT155	155	2000	15	NA	no	manual	none	-40	70	Plaintree
WAVEBRIDGE XT T1/E1	1 x 2.048	4000	15	NA	no	manual	none	-40	70	Plaintree
WAVEBRIDGE XT T4/E4	4 x 2.048	3000	15	NA	no	manual	none	-40	70	Plaintree
SkyLINK	1250	1600	5.1	15	no	manual	none	-40	65	SkyFiber
SkyLINK Plus	1250	1600	5.1	15	yes	manual	none	-40	65	SkyFiber
LaserFire	1000	5000	6.4	20	no	auto	auto	-55	85	Space Photonics
LCT-135	5650	45000000	53	160	no	auto	auto	NA	NA	Tesat

A.2 DYNAMIC FSO SYSTEMS

FSO System Name	***Max Bandwidth (Mbps)***	***Max Oper Dist (m)***	**Weight (kg)**	***Max Pwr Cons (W)***	**Hybrid**	**Pointing**	**Tracking**	**Min Op Temp(C)**	**Max Op Temp (C)**	**Contact**
LCT-135	5650	45000000	53	160	no	auto	auto	NA	NA	Tesat
MLT-20	1000	50000	5	NA	no	auto	auto	NA	NA	ViaLight
MLT-100	1000	600000	25	NA	no	auto	auto	NA	NA	ViaLight
Fast Airborne Laser Communications Optical Node FALCON	2500	130000	NA	NA	no	auto	auto	NA	NA	AFRL
Ball Aerospace	NA	NA	NA	NA	no	auto	auto	NA	NA	Ball Aerospace
AOptix Aerostat	80000	NA	20.5	28	no	auto	auto	NA	NA	AOptix Technologies Inc.
TALON	10000	50000	NA	NA	no	auto	auto	NA	NA	EXELIS
Compact Interrogator (CI)	2000	50000	25	100	no	auto	auto	NA	NA	NovaSol
Lunar Laser Communication Demonstration (LLCD)	622	384,633,220	NA	NA	no	auto	auto	NA	NA	NASA

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APPENDIX B. LASERFIRE EXPERIMENT AT CAMP ROBERTS, CA

B.1 DESCRIPTION

This experiment was conducted over a four day period during the Joint Interagency Field Exploration (JIFX) 14-4 at Camp Roberts, CA. It was done in partnership with the Space and Naval Warfare Systems Command (SPAWAR) San Diego, CA and SpacePhotonics Inc., based in Fayetteville, AR. SPAWAR provided a research advisor and two LaserFire V3 units. A single LaserFire V3 unit is shown in Figure 53. SpacePhotonics Inc. provided a technical expert and an earlier version of the LaserFire they referred to as the “camo” boxes due to their camouflage paint scheme, shown in Figure 54.

Figure 56. LaserFire V3 unit. Transmitter (left), modem (center), optical and power cable spool (right).

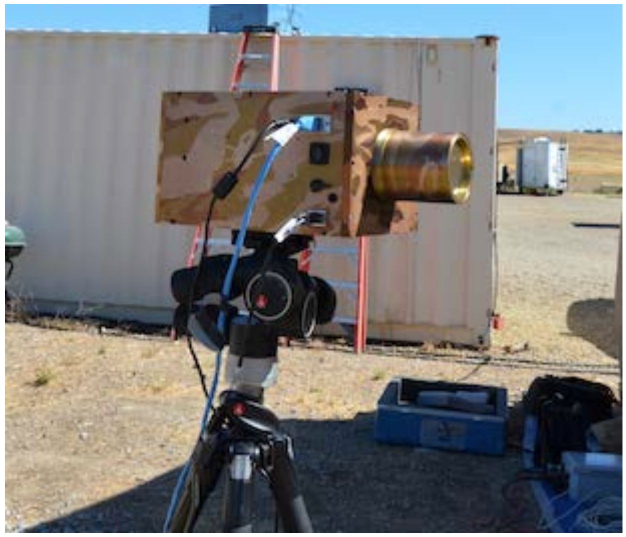

Figure 57. LaserFire “camo” unit mounted on a tripod.

B.2 PURPOSE

The SpacePhotonics Inc. product information webpage claims a bandwidth of 1 Gbps over a range of 5 km from their current LaserFire system [75]. The most current LaserFire system is the V3 system. They also claim that the beam can be tracked within a 30-degree two-dimensional cone field of regard. This field of regard is substantially greater than other static systems and is achieved without the use of gimbals, turrets or steering mirrors [75]. With a field of regard this large it may be possible to use this system in dynamic vice static applications. The goal of this experiment was to test this hypothesis, the general static performance of the system, and the system’s ability to complete a network hop between two links. Ultimately, the goal was to establish a link as shown in Figure 54. Additionally, the experiment served as a hands-on introduction to FSO for the Center for the Study of Mobile Devices and Communications at the Naval Postgraduate School.

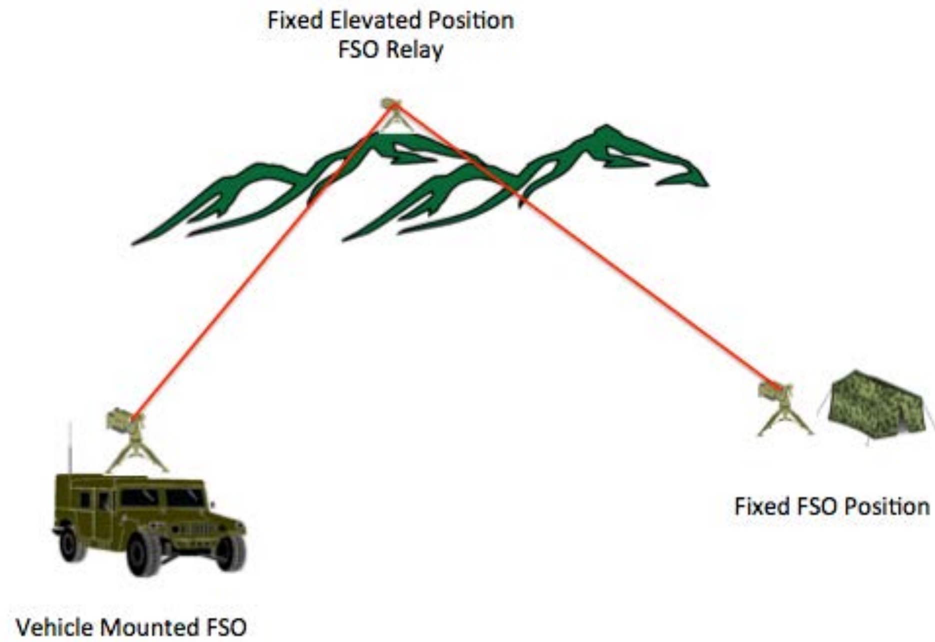

Figure 58. OV-1 Diagram for experiment.

B.3 EXECUTION

1. Day 1

The first part of day one was spent checking into JIFX and updating the software on the two LaserFire V3 units. Once the software update was completed two links were setup in parallel on the side of a road east of the McMillan Airfield facility, shown in Figure 53. The range of both links was 100m.

Figure 59. Day 1 FSO link diagram.

Initially, there was some difficulty establishing the links. This was due to the beams becoming crossed between the two systems with the V3 system locking onto the “camo” system and vice versa. This problem was identified once the systems indicated that the links were established, but a ping test from one end to the other was unsuccessful. Blocking one of the beams and checking the link status easily confirmed that the beams were crossed. To prevent crossing beams again, one system was covered while the other system conducted its search pattern. Once both links were operational, a two-hop link was established from site 1, to site 2, and back to site 1. The integrity of the two-hop link was initially tested with a ping test. Following a positive ping test, FMV was successfully passed through the link. The quality of the video was good. However, some jitter was observed. By the time the link was established it was nearly 1630 and the conditions were hot and windy. The mirage effect, typical in conditions with high levels of scintillation, was easily observable.

2. Day 2

Day two began by setting up a longer link, 750m, along a dusty road west of McMillan Air Facility, shown in Figure 54. Weather conditions were nearly identical to day 1. The link was set up in the same fashion as the link on day one. At this distance the “camo” units were able to establish a lossy link. This was expected given the hot conditions and the known performance of the system. The LaserFire V3 unit was able to maintain a fairly strong link initially, and ping tests and jittery video were once again transmitted over the two-hop link to confirm its integrity. However, as the day progressed the LaserFire V3 unit’s performance began to degrade due to equipment overheating issues. The LaserFire V3 unit, shown in Figure 53, has a 1-gigabit network card that has a max operating temperature of 50 degrees Celsius. This card is enclosed in a modem box separate from the transmitter. Both transmitter and modem are completely enclosed with nothing in place to dissipate heat besides the aluminum construction of the boxes. Under normal operating conditions the network card heats up, and in high ambient operating temperatures, this is exacerbated. When the system overheats, it automatically shuts off. Overheating also caused corruption of the network settings, which had to then be reconfigured. Once the system shutdown due to overheating, it was opened and placed in the shade for a period of time to cool off. Periodically, motor vehicles would travel down the road kicking dust into the air and in the beams path. Link degradation during these periods was observed via the systems GUI Optical Power Log. Also, if the vehicle passed through the beam LOS was lost and the link was dropped. When this occurred the systems would automatically try to reacquire the link with a high rate of success.

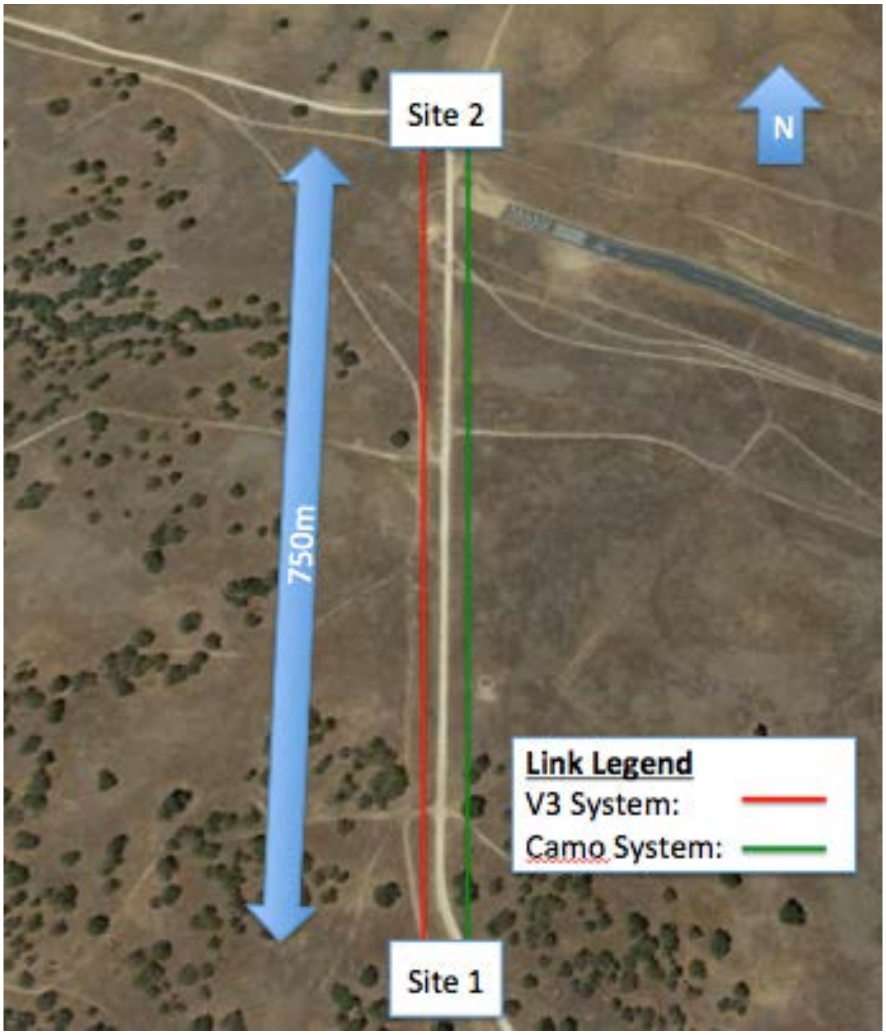

Figure 60. Day 2 link diagram A.

Later in the afternoon of day two, a longer link, 1150m, was established using the LaserFire V3 system. This link diagram is shown in Figure 56. This link was fairly lossy. Overheating continued to be an issue, and the systems were put in the shade with the modem box cracked open to try and mitigate this.

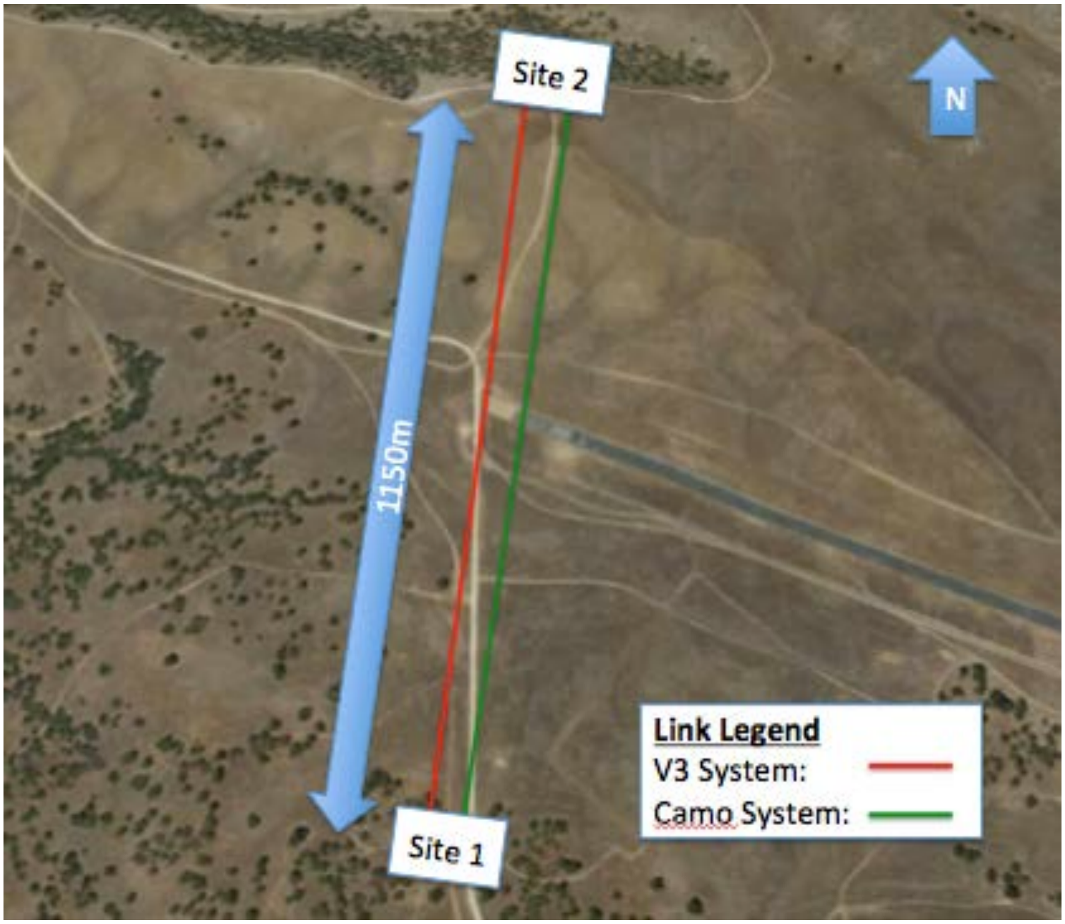

Figure 61. Day 2 link diagram B.

3. Day 3

On day three, a two-hop link was set up from a hill northwest of the air facility about 1350m away with the LaserFire V3 units, to a position southeast of the air facility about 150m using the “camo” units. Again, weather conditions remained consistent. The link between the “camo” boxes was established quickly and worked well with both ping and video tests. By the time the link from the hilltop to the air facility was established the internal temperatures of the LaserFire V3 units were already at 46 degrees Celsius. This was an indication that overheating might again be an issue. The two-hop link was confirmed using ping tests, but the packet loss was as high as 90 percent. The link was not able to support FMV.

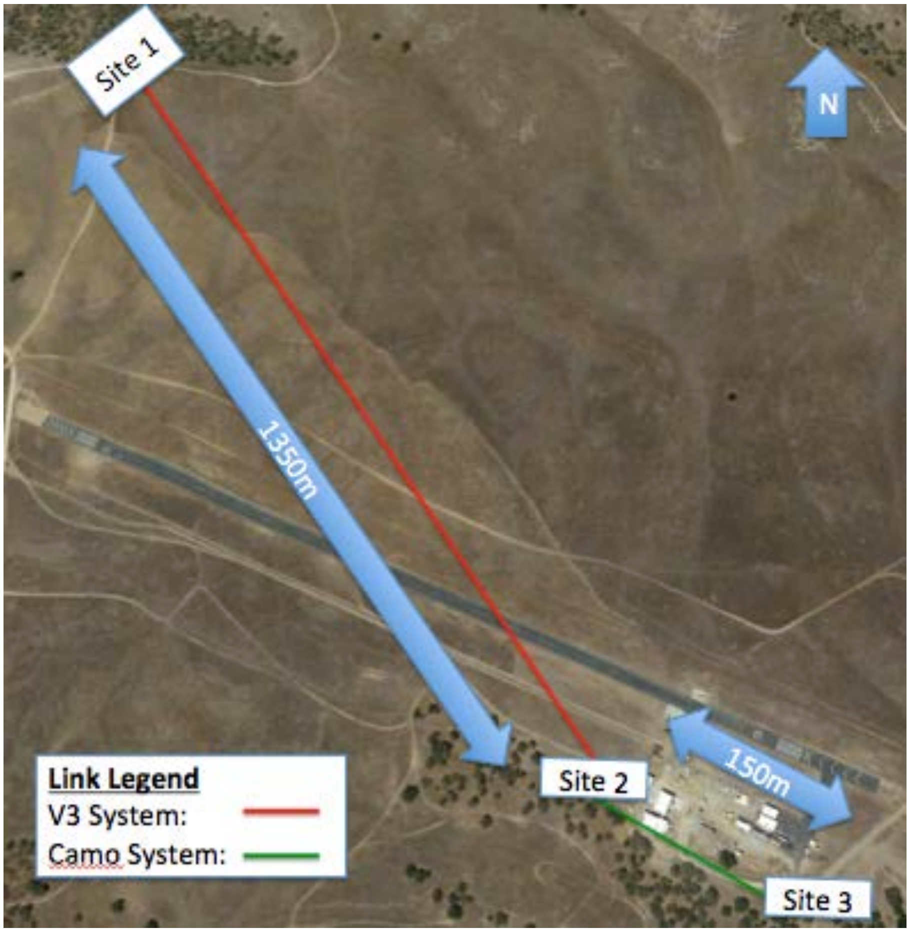

Figure 62. Day 3 link diagram.

4. Day 4

The goal for day four was to establish the same link from the hilltop to the air facility as day three, shown in Figure 58, and collect bandwidth data using the Iperf TCP/UDP Bandwidth Measurement Tool. The testing conducted sent data one way through the link effectively testing only a half-duplex capability. Weather was again consistent with the previous three days.

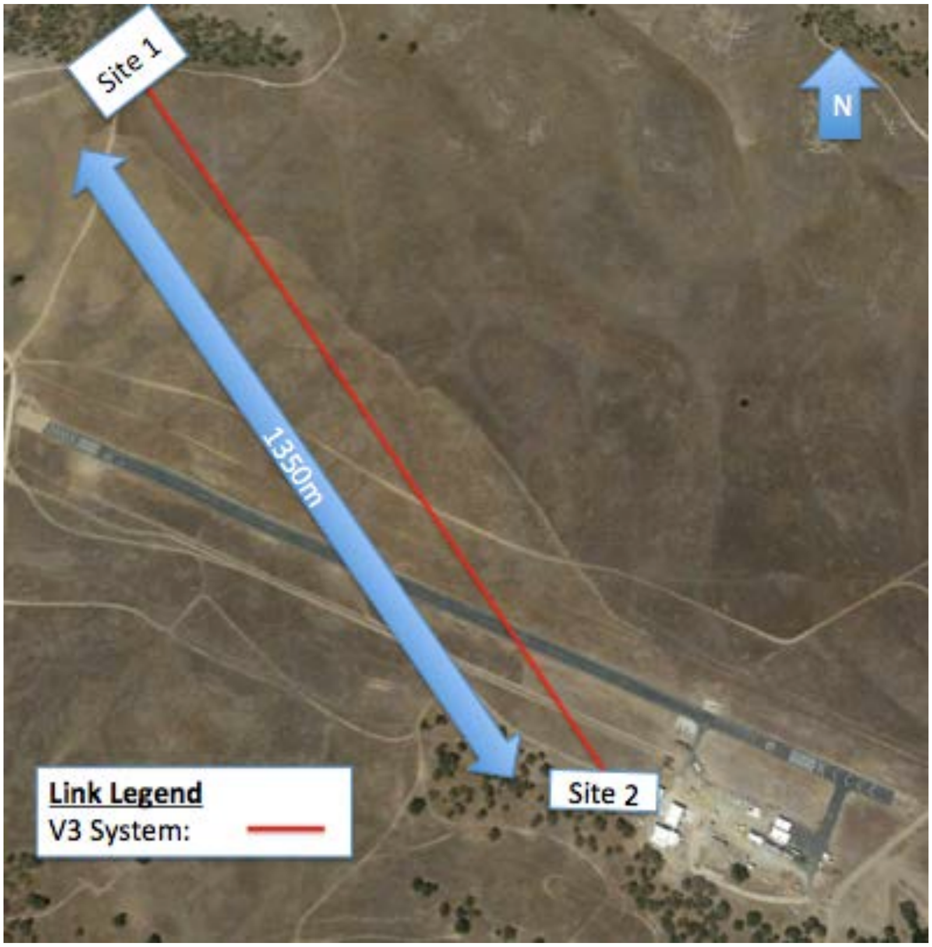

Figure 63. Day 4 link diagram.

The link was established as quickly as possible in the attempt to beat the afternoon heat. Once the link was confirmed using ping tests the Iperf testing began. The server, the station sending the data, was located at site 1, and the client, the station receiving the data, was located at site 2. The first test was started at 0945 with an ambient temperature of 19 degrees Celsius. This test was conducted for 620 seconds sending TCP traffic. During this test a total 21.9 Gbits were transmitted at an average bandwidth of 0.3 Gbps. Figure 59 is a graph of the data transferred and bandwidth over the duration of the test from the server.

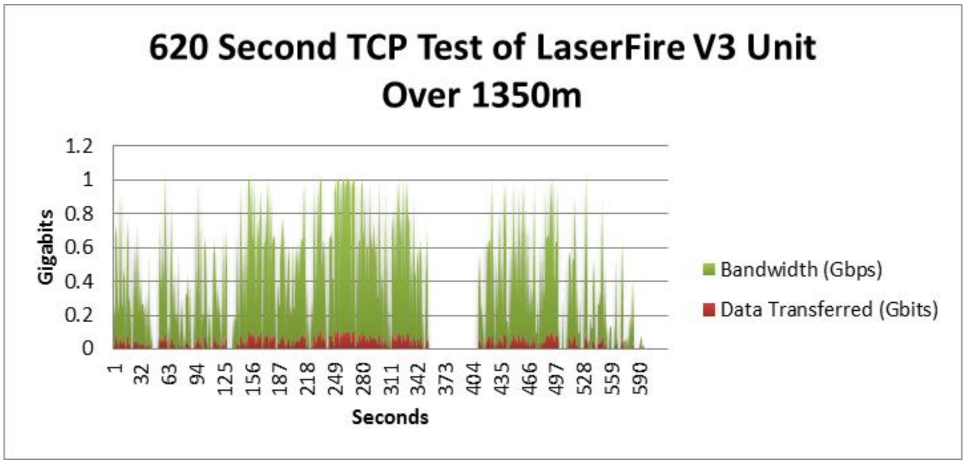

Figure 64. 620 second TCP test of LaserFire V3 unit.

The second test conducted began at 0955 with an ambient temperature of 21 degrees Celsius. This test was 600 seconds in duration sending UDP traffic. The total amount of data transferred during this test was 51.9 Gbits at an average bandwidth of 0.74 Gbps. This seems considerably better than the TCP test, but there was no way to tell how much of this data actually got through. The client end of the link did not even register that a test was occurring. A plot of the data sent and bandwidth over time for the UDP test is shown in Figure 60.

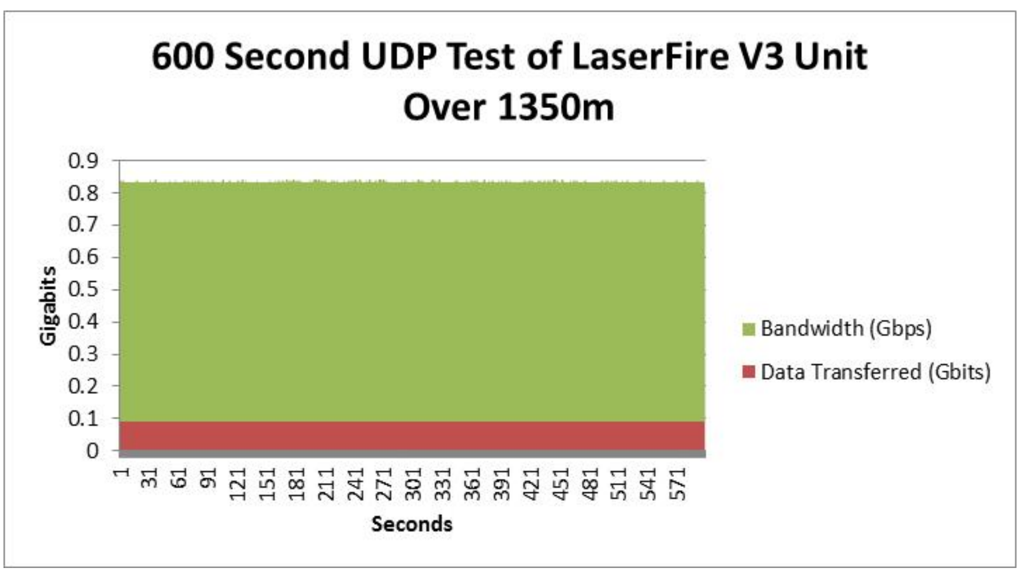

Figure 65. 600 second UDP test of LaserFire V3 unit.

During both the first and second tests, a ping test was also simultaneously conducted. The results of this test were a total of 3115 packets transmitted, 2361 of those packets were received yielding a 24.2% packet loss. A snapshot of the Optical Power Log was also taken at the completion of the tests and is shown in Figure 61.

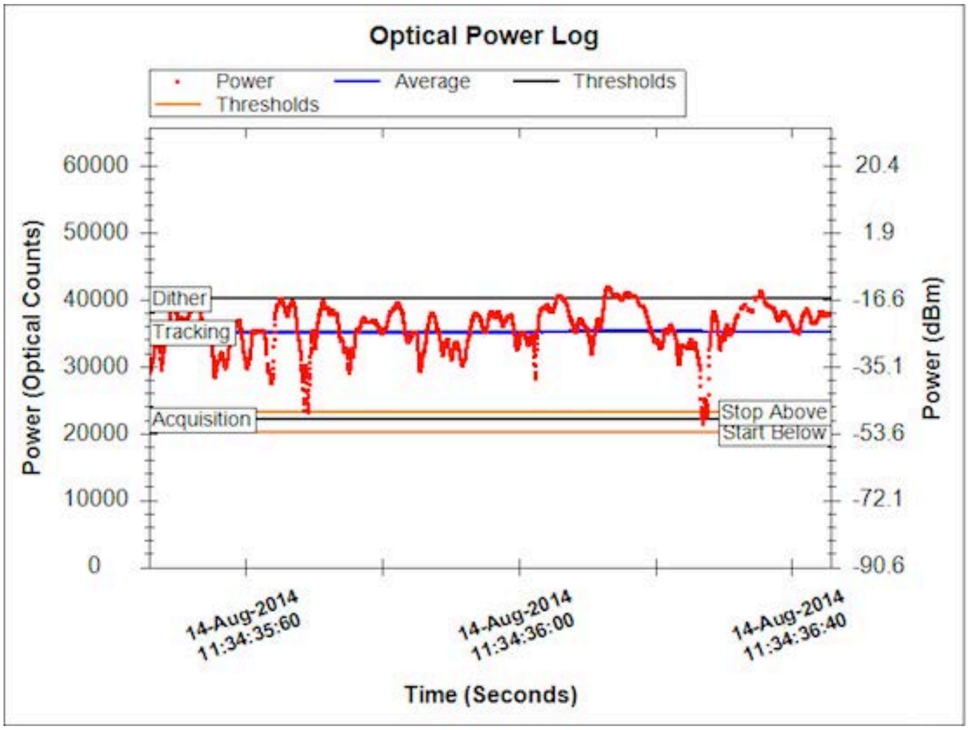

Figure 66. Optical Power Log snapshot during 620 TCP test.

The third test ended up being the last test conducted that day due to the system overheating. This test began at 1140 with an ambient temperature of 25 degrees Celsius. This test lasted 517 seconds of a planned 600 seconds before the unit shutdown. Total data transmitted and average bandwidth was not available since the test was not completed. However, there was basically no data being transmitted during this test. The graph bandwidth and data transmitted over time for this test is shown in Figure 62.

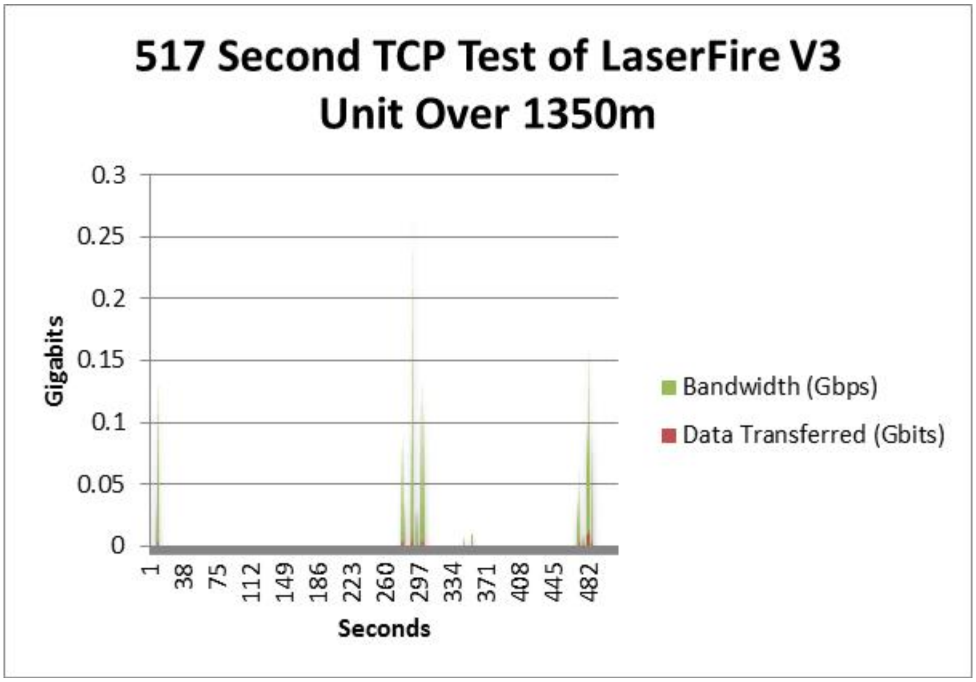

Figure 67. 517 second TCP test of LaserFire V3 unit.

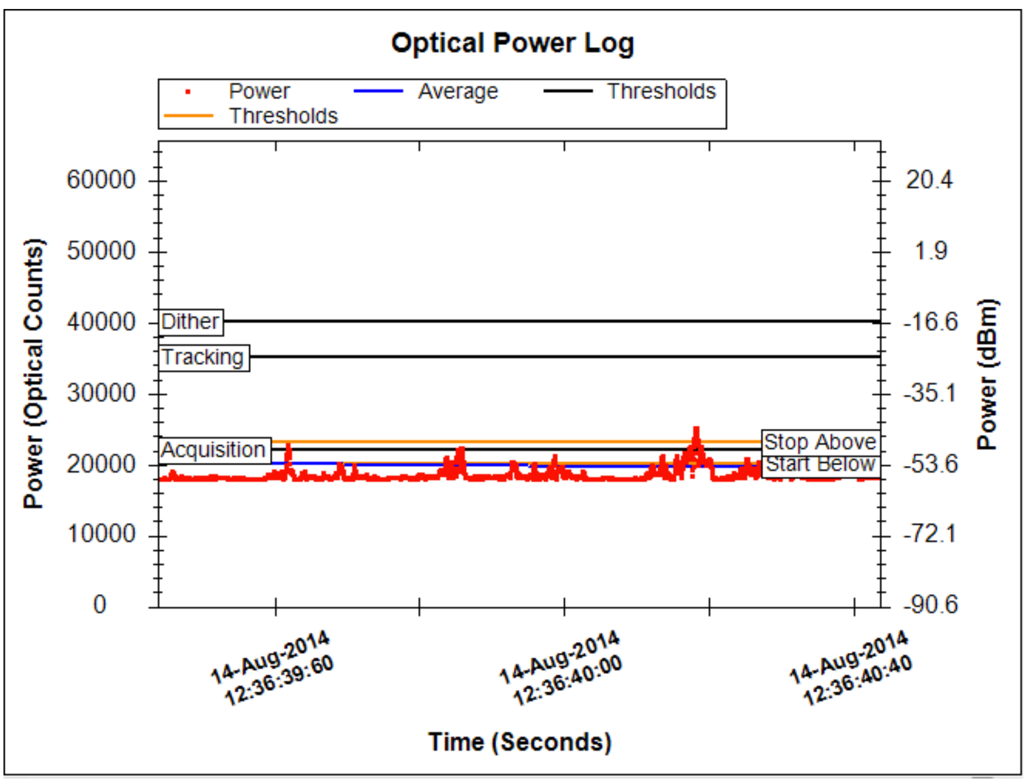

Figure 68. Optical Power Log snapshot during 517 second TCP test.

B.5 CONCLUSION AND RECOMMENDATIONS

The LaserFire system is not currently ready for deployment nor would it be a viable option for dynamic links in its current configuration. There are several issues that need to be addressed before the system could be used in an operational setting. First, the issue of overheating must be addressed. Second, link acquisition must be sped up. Third, the size of the system must be reduced. Finally, data rate should be made adjustable allowing for optimizing the transmission rate according to the link performance as measured by signal-to-noise ratio or packet loss.

The design of the LaserFire V3 needs to be improved to allow for greater dissipation of heat from elements inside the modem and transmitter boxes. Currently, the boxes are completely sealed. Their aluminum construction provides some relief due to its relatively high conductivity, however this alone is nowhere near sufficient. On day four at the hill site, the transmitter and modem were placed in the shade and in well-ventilated positions. Both were cool to the touch on the outside of the box. However, the modem still shut down due to overheating. Upon inspection it was found that the network card inside the modem was the only element hot to the touch.

Initial link acquisition is a fairly time consuming process. It requires the operator to manually align the two units and then initiate an automated search pattern. Once the pattern is initiated the amount of time to acquire varies depending on how well the units were aligned manually and the system's search configuration. There were several instances where the search pattern failed to identify the opposite end of the link and had to be restarted. Additionally, during testing there were several instances where the LOS of the link was interrupted either by someone walking through the beams path or a car driving through it. In nearly every instance this caused the link to drop and sent the system into an automatic reacquisition search pattern. Incorporating the use of Global Positioning System (GPS) coordinates, increasing the search area through adjustable beam divergence, and by implementing an interrogation protocol that

allows the system to identify it has established link with the correct unit may help in speeding up the acquisition process. A dynamic application would not be possible without near instantaneous link reacquisition.

In order to increase link quality the user should have the ability to dial back the bandwidth. If a high rate of packet loss is experienced at a 1 Gbps bandwidth, adjusting the bandwidth to 100 Mbps may improve link quality. A bandwidth of 100 Mbps is sufficient for nearly every application and greater than most RF options.

It is recommended to continue research and development efforts with SpacePhotonics Inc. as well as exploring other FSO systems.

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